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DETERMINATION OF AEROSOL CONTENT IN THE ATMOSPHERE FROM LANDSAT DATA

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FOREWORD

This report documents the research performed under Contract NAS5-20899 between 29 January 1975 and 28 January 1978. The Principal Investigator was Dr. M. Griggs who is indebted to Mr. M. R. Schoonover for his computer programming, and to Mr. G. Hall for making some of the ground-truth measurements. Dr. Griggs also wishes to thank Mr. E. Flowers of NOAA and Dr. D. Pitts of NASA for providing ground-truth measurements from their turbidity networks. Special thanks are due to Mr. H. Oseroff, the technical monitor, for his considerable administrative assistance in this investigation.

DETERMINATION OF AEROSOL CONTENT
IN THE ATMOSPHERE FROM
LANDSAT DATA

M. Griggs
Science Applications, Inc.

SUMMARY

A large set of Landsat 2 data, obtained at San Diego, showed excellent linear relationships, particularly for MSS5 and MSS6, between the radiance over the ocean and the atmospheric aerosol content. Two other data points obtained at Adrigole, Ireland, representing a different ocean and a different ground-truth instrument, showed very good agreement with the San Diego data. Thus, it appears that the technique could be used for global monitoring of the atmospheric aerosol content over the oceans. The Landsat 2 results at Miami, in contrast to the Landsat 1 results, tend to show a different linear relationship, perhaps due to a different type of aerosol in that region. However, the Miami results must be used cautiously due to possible bottom-reflectance effects.

The results obtained at several inland bodies of water showed that MSS4, MSS5 and MSS6 cannot be used due to the effect of water pollution (natural or man-made) generally present. However, the Landsat 1 results suggest that MSS7, which operates at longer wavelengths, is not very sensitive to water pollution, and might be useful for inland measurements of aerosol content. The use of the longer wavelength would also minimize the effects of adjacent high albedo land, since atmospheric scattering is reduced at longer wavelengths. However, the results for MSS4, MSS5 and MSS6 indicate that this effect is small even at the shorter wavelengths.

It is recommended that this technique should be developed for operational use to monitor the global distribution of the atmospheric

aerosol content over the ocean. Knowledge of the aerosol distribution and its variations will greatly aid climatic studies of long-term predictions of warming or cooling trends. Existing or planned satellites, with narrow bandpass visible radiometers, such as NOAA, GOES and TIROS N, can be used for global monitoring. However, if a choice of bandpass is possible, the Landsat results suggest that a bandpass of 0.1 μm centered in the vicinity of 0.65 or 0.75 μm would be preferred. It would be desirable also to add a bandpass in the near infrared around 0.9 μm, since the Landsat 1 results indicate that the bandpass might provide information over polluted inland water as well as over the oceans.

1. INTRODUCTION

In recent years the awareness of the importance of atmospheric aerosols in possible climate modification has spread from the scientific community (SCEP[1] and SMIC[2]) to the public sector.[3] However, it is still not clear whether the global aerosol content is increasing significantly, and exactly what effect aerosols have on climate.

McCormick and Ludwig[4] presented evidence of a world-wide buildup of atmospheric aerosols which could increase the earth albedo resulting in a cooling of the earth/atmosphere system. This effect would counteract the postulated increase of temperature in the lower atmosphere due to the "greenhouse effect" of the increased CO_2 emissions by human activities. In fact, there has been a decrease in the mean annual air temperature since about 1945 at Northern mid-latitudes, suggesting that the aerosol pollution effect is greater than that of the CO_2 increase. However, the effects of aerosols and CO_2 are more complex than suggested above, so that their effects on climate are not readily predicted. For instance, Robinson[5] points out that the earth may self-regulate its temperature by the variation of cloud amount: the higher temperatures, due to the CO_2 "greenhouse effect", lead to a higher water content in the lower atmosphere, which may increase the cloud amount; this increases the albedo, thereby decreasing the temperature. Robinson concludes there is no justification for forecasting a final equilibrium temperature due to an increase in CO_2 content, until atmospheric models are significantly improved to include the cloud cover as a variable.

In addition to the uncertainties in the climatic effects of CO_2, the cooling effect of aerosols suggested by McCormick and Ludwig may not be correct. Charlson and Pilat[6], Atwater[7] and Mitchell[8] have shown that since aerosols absorb and scatter, they may produce warming or cooling, depending on the ratio of absorption to scattering. However, it is suggested by Twomey[9] that increased aerosol densities may produce increased cloud cover with resultant cooling effects, which could dominate the warming effects due to aerosol absorption.

Thus, it is clear that considerably more work on the complex problem of modeling the atmosphere and on the optical properties of aerosols is needed before the long term effects of man-made pollution can be predicted. Since these problems will not be solved in the near future, it is important to initiate global measurements of aerosols on a continuous basis to monitor any changes.

A satellite technique using visible radiance measurements over water surfaces was suggested by us for global monitoring as a result of early theoretical studies;(10) the feasibility of the technique was investigated in a Landsat 1 study.(11,12) These studies suggested, as illustrated in Figure 1-1, that a linear relationship exists between the upwelling radiance, measured in the MSS bands over water surfaces, and the atmospheric aerosol content. The aerosol content is defined in terms of the Elterman 1964 model vertical aerosol optical thickness; i.e., the aerosol content is given by the ratio (measured aerosol optical thickness at wavelength λ/model aerosol optical thickness at wavelength λ).

The present investigation is an effort to use Landsat 2 data to confirm the previous findings, and to check the relationships at different sites. The San Diego and Salton Sea test sites of the Landsat 1 investigation were used again, and were supplemented by other NOAA-EPA turbidity network sites and by some NASA LACIE sites.

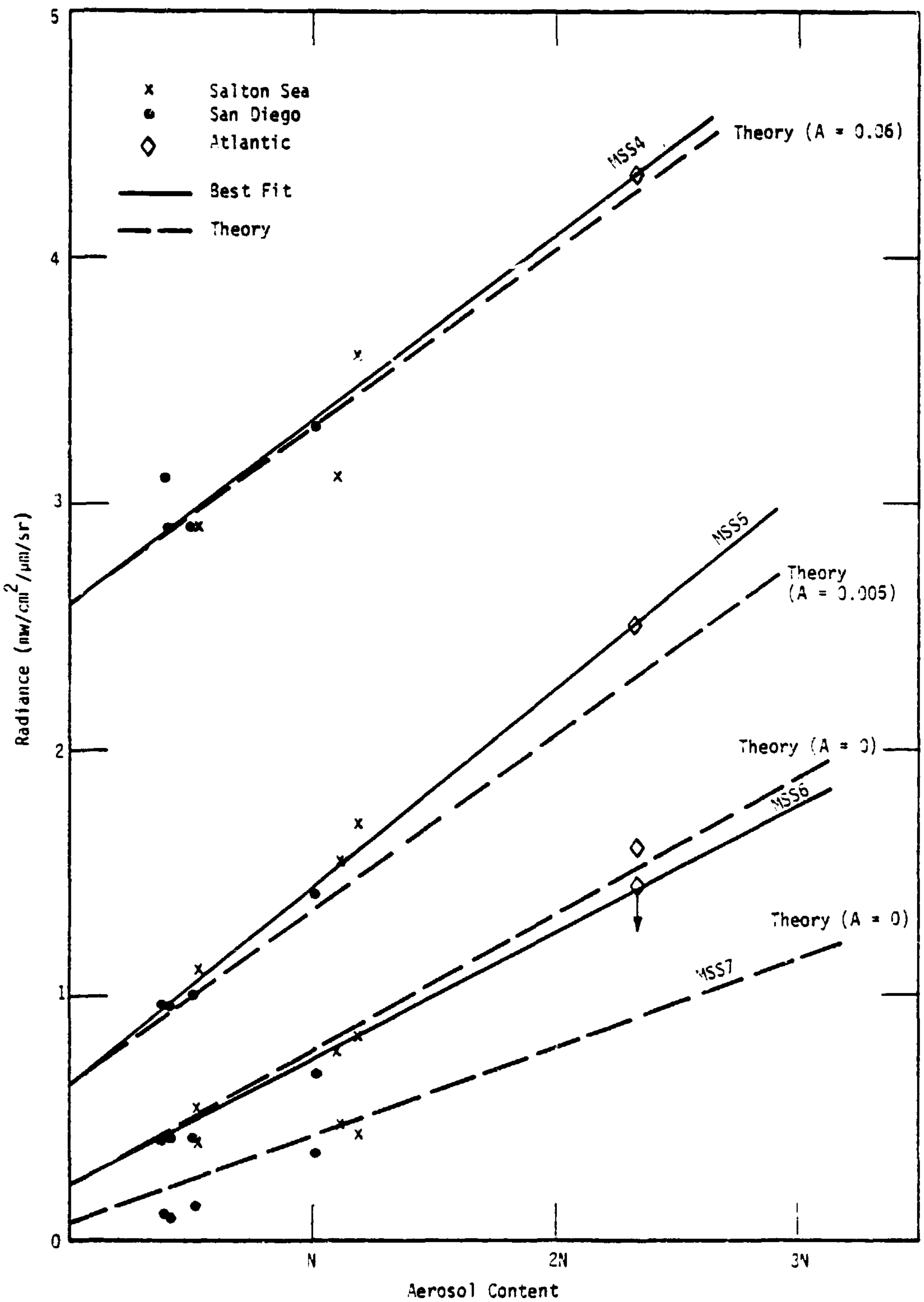


Figure 1-1. Landsat 1 Data Compared to Theoretical Calculations.

2. APPROACH

The approach to the investigation is essentially the same as that described for the previous Landsat 1 program,(11) i.e., an empirical one based on theoretical calculations for model atmospheres. To make the computations manageable, certain approximations about several parameters, such as the aerosol size distribution and the underlying surface reflectance, have to be made. Hence, in the real atmosphere, model conditions are never realized, so that deviations from the theoretical relationships are expected. Thus, an empirical investigation has been conducted using the theory to provide insight into the extremes of values which may be encountered.

The main thrust of the study has been to further investigate the radiance-aerosol content relationship. A secondary purpose was to determine the feasibility of using contrast measurements in urban areas to determine the aerosol content. Both investigations were to be supported by surface radiance measurements made from a low-flying aircraft.

The satellite radiance measurements were obtained from the Landsat digital data, and the ground-truth measurements of the aerosol content were made with a Volz photometer at the time of selected Landsat overpasses. The surface radiance measurements were made with an Exotech radiometer mounted in a low-flying aircraft.

2.1 Theoretical Relationship of Radiance and Aerosol Content

The basic theoretical radiance-aerosol content relationship was described in the Landsat 1 study.(11) The present calculations with the Dave(13) atmospheric scattering program have been used to determine the effect of aerosol properties on the radiance-aerosol content relationship. These properties include the aerosol size distribution, real and imaginary refractive indices, and the vertical distribution of the aerosols.

2.1.1 Size Distribution Effects

The Dave program is designed to handle three types of aerosol size distributions, and we have investigated the two most commonly used for atmospheric aerosols, viz. the Junge and log-normal distributions.

The Junge distribution has a constant number density below 0.1 μm radius, and above 0.1 μm follows a power law distribution:

$$dn(r) = Cr^{-\nu} d \log r \ (cm^{-3}) \tag{2-1}$$

where $n(r)$ is the number of particles with radius r, and C is a constant depending on the number of particles per unit volume.

A value of $\nu = 3$ is generally accepted as most closely representing natural aerosol distributions.

Calculations were made for different values of ν, keeping all other aerosol parameters constant. The effect of changing ν is shown in Figure 2-1, where the results for $\nu = 2$, 3 and 4, for a refractive index of 1.5-0i, are presented for the MSS6 bandpass in comparison with the measured Landsat 1 data, obtained in our previous Landsat investigation.

It is seen that the measured data agree well with the theoretical results at $N = 0$ (i.e., a Rayleigh atmosphere) for zero albedo ($A = 0$), rather than for $A = .02$, the hemispherical albedo of water. This is expected since water is a specular reflector, so that the water reflectance in the nadir is much less than .02, and closer to zero. The measured variation of radiance with aerosol content is best represented by an aerosol size distribution with ν larger than 3; Yamamoto and Tanaka[14] found $\nu = 3.57$, Ward et al.[15] found $\nu = 3.5$, and Shaw et al.[16] found $\nu = 3.32$.

The log normal distribution (e.g. Russell and Grams[17]) may typically be represented by:

$$n(r) = \left[\sigma r (2\pi)^{\frac{1}{2}}\right]^{-1} \exp\left[-(\log_e r - \log_e r_m)^2 / 2\sigma^2\right], \quad r_{min} \le r \le r_{max} \quad . \tag{2-2}$$

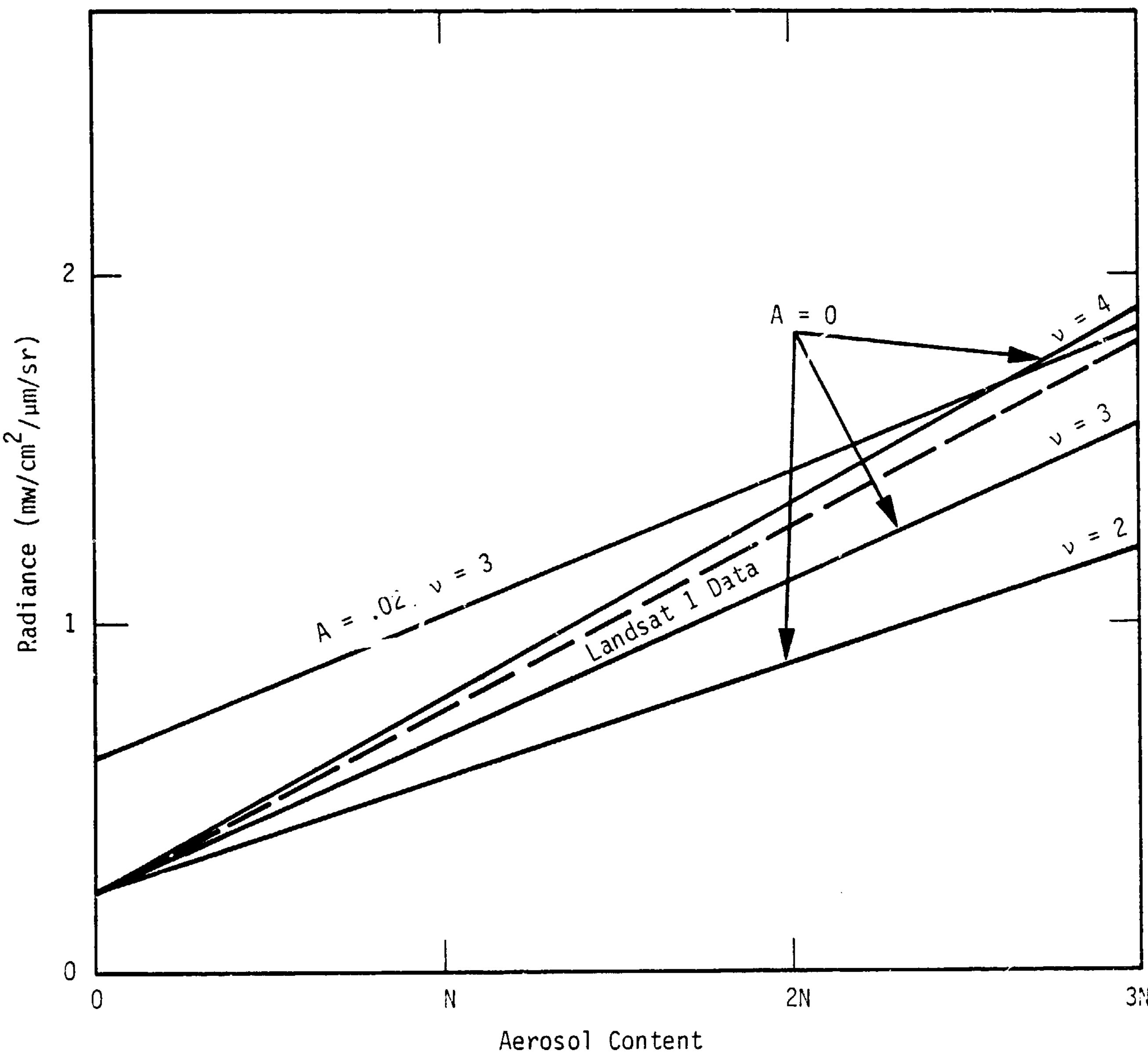


Figure 2-1. Measured (Landsat 1) and Calculated Radiance for MSS6 (0.75 μm).

For the log-normal distributions, values of r_{min} and r_{max} are computed from the following expressions:

$$r_{min} = \exp(\log_e r_m - 4\sigma) \quad , \tag{2-3}$$

and

$$r_{max} = \exp(\log_e r_m + 4\sigma) \quad . \tag{2-4}$$

Using the same particle radius limits as our previous calculations for the Junge distribution, i.e., $r_{min} = .03$ μm and $r_{max} = 8.5$ μm, we find that $\sigma = .7058$ and $r_m = .505$ μm. This distribution is compared to the Junge ($\nu = 2$) distribution in Figure 2-2.

The results of this calculation for MSS6 are plotted in Figure 2-3 in comparison with the previous calculations for the Junge distribution. It is seen that the log-normal distribution gives radiances similar to those for the Junge ($\nu = 2$) distribution, and significantly lower than the measured Landsat 1 relationship which corresponds to a Junge ($\nu = 3.7$) distribution. The calculations were performed for a refractive index of 1.5 - 0i. If aerosol absorption (Section 2.1.3) were introduced, the radiance values would decrease, making the difference from the measured data even greater. Hence, the Landsat data suggest that a single log-normal distribution, covering this particle size range, does not provide a good description of the backscattering by atmospheric aerosols.

2.1.2 Refractive Index Effects

Calculations were made with the Dave program to determine the effect of changing the real part (n) of the refractive index on the radiance-aerosol content relationship. In all the previous calculations $n = 1.5$ has been used as being representative of typical atmospheric aerosols.(18) This value will decrease when the humidity increases above about 80% due to condensation on the aerosols. The value $n = 1.4$ is reached at about 98% humidity. Thus calculations for $n = 1.4$ have been

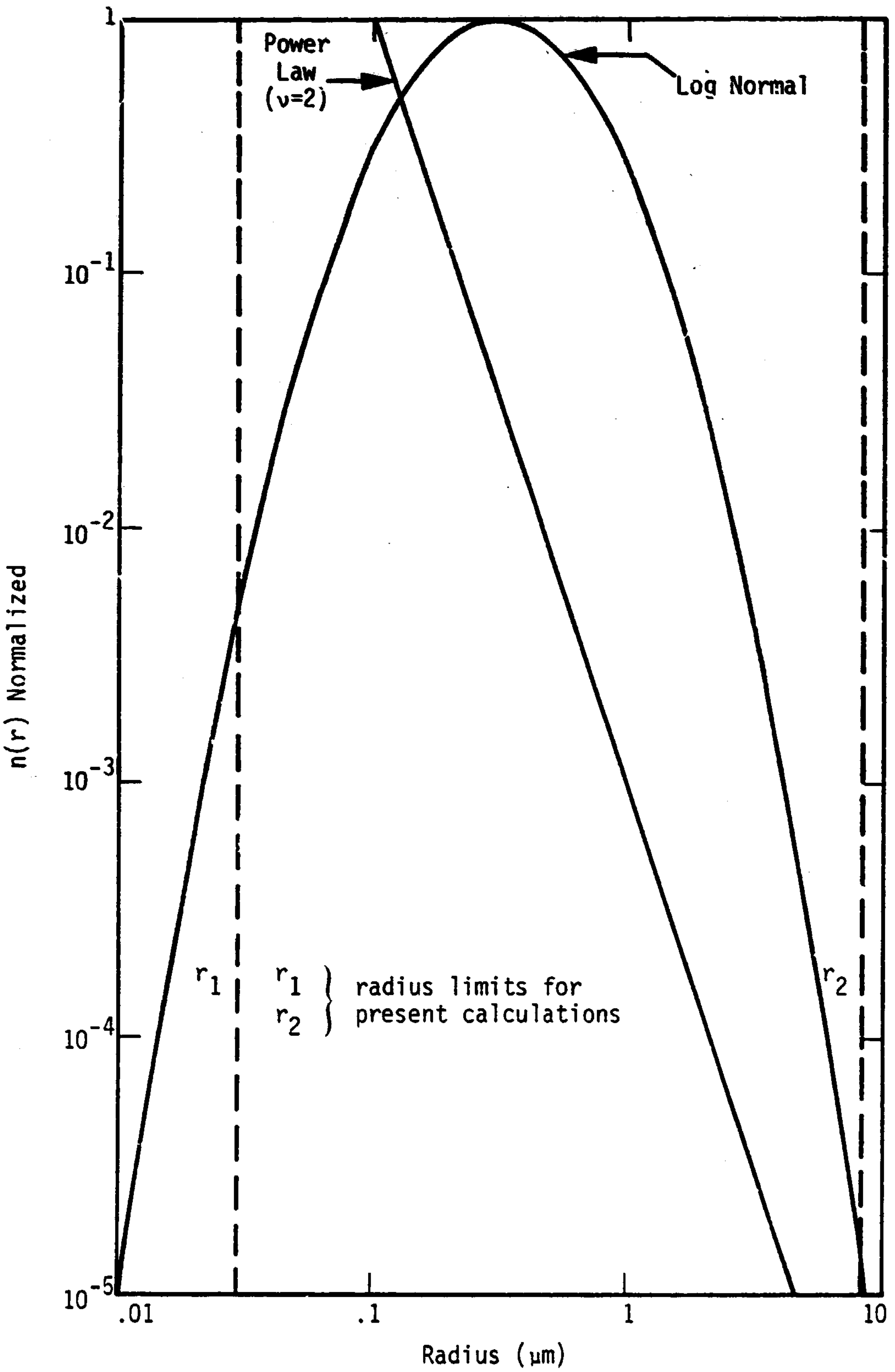


Figure 2-2. Particle Size Distributions.

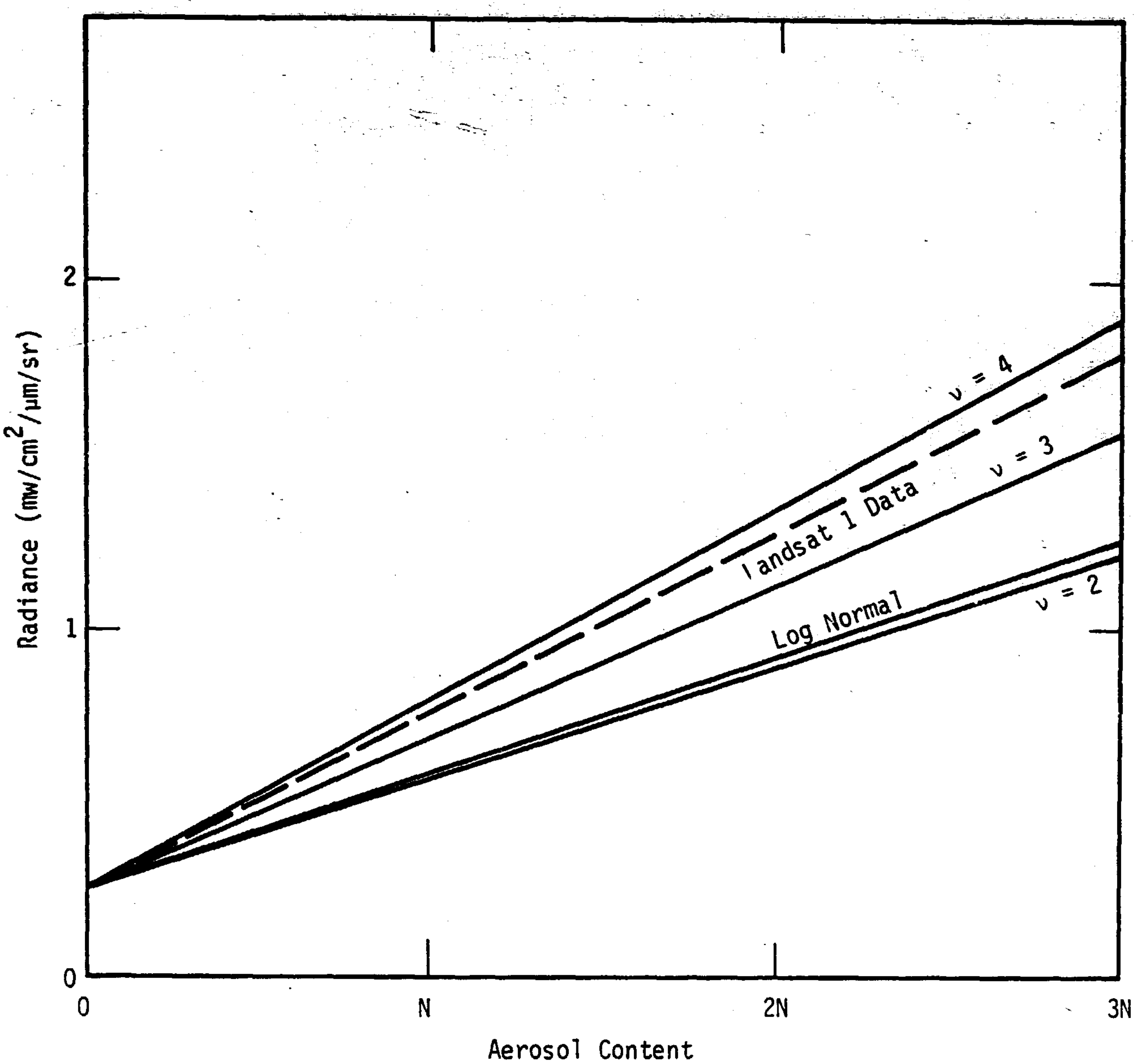


Figure 2-3. Measured (Landsat 1) and Calculated Radiance for MSS6 (0.75 µm).

made since this is probably an extreme variation of refractive index. The results for $n = 1.4$ are shown in Figure 2-4 in comparison with the previous calculations for $n = 1.5$ (for $\nu = 3$). It is seen that this change in refractive index produces a small but significant change in the radiance values. This was not expected since the scattering function for a distribution of aerosol sizes was thought to be relatively insensitive to the refractive index (e.g. Bullrich[18]). Little work appears to have been done to determine the range of values for the refractive index of aerosols, but Bullrich estimates that it will generally be in the range 1.49 to 1.59, for normal humidities.

2.1.3 Aerosol Absorption Effects

The Dave program was used to investigate the effect of aerosol absorption on the radiance-aerosol content relationship, assuming a Junge size distribution. Absorption is included in the calculations by making the imaginary part of the refractive index non-zero. A survey of the literature suggests that for aerosols, away from industrial sources, the imaginary part does not exceed .01 (e.g. Volz[19], Bergstrom[20], and Grams[21]). Hence a refractive index of $n = 1.5 - 0.01i$ was used in the calculations. The results shown in Figure 2-5 indicate that, for a size distribution with $\nu = 3$, the absorption reduces the upwelling radiance by about 11% for normal aerosol contents. (The absorption optical thickness is about 9% of the total vertical attenuation optical thickness.) This radiance change of 11% would be interpreted as a reduction of about 16% in the aerosol content if absorption were assumed to be absent.

Thus, while the effect of aerosol absorption does not appear to be large (it could, of course, be larger in the vicinity of industrial particulate emissions), it does raise the question of the interpretation of the data in our Landsat 1 program: Could absorption effects be disguising the effects of sun glitter? (i.e., Could sun glitter increase the upwelling radiance which is then reduced by absorption effects?) On the basis of published data on aerosol optical properties, it would

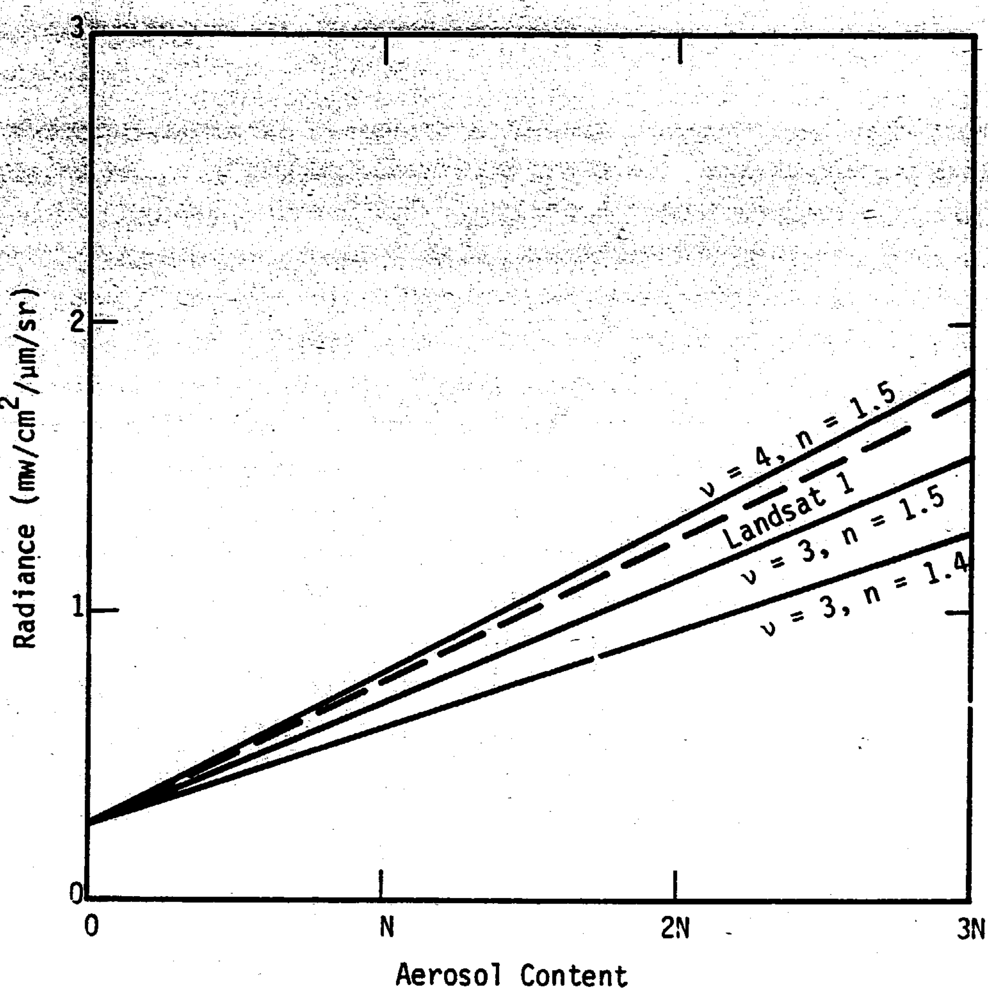


Figure 2-4. Measured (L‌andsat 1) and Calculated Radiance for MSS6 (0.75 μm).

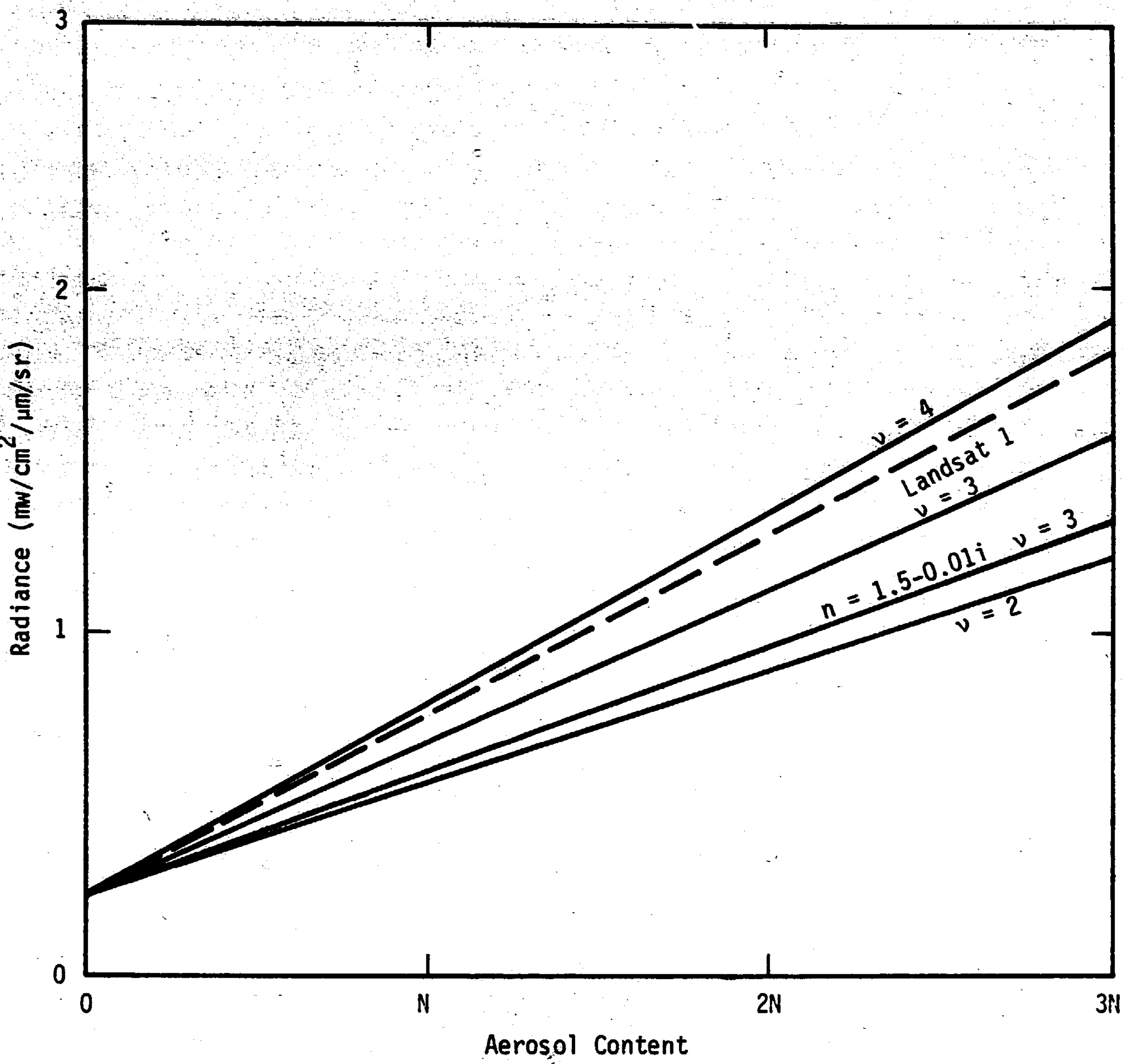


Figure 2-5. Measured (Landsat 1) and Calculated Radiance for MSS6 (0.75 µm)

appear that aerosol absorption effects are not significant in the Landsat radiances. The one data point which might exhibit sun glitter effects is the Atlantic point of high aerosol content.[11] This high aerosol content was due to Sahara dust, presumably predominantly silicate particles, which have a zero imaginary component in their refractive index.[20,22] Thus, no absorption effects are expected for this data point. It should be noted that observations over the ocean are not affected by absorption by sodium chloride particles, which also have no imaginary component in their refractive index.

2.1.4 Vertical Distribution Effects

In our early theoretical studies,[10] on the basis of Monte Carlo calculations made for us by Plass and Kattawar,[23] we showed that the radiance-aerosol content relationship is independent of the height distribution of the aerosols. Those original calculations had considered only variations below 1 km. The present calculations (for MSS6), with the Dave program using the log-normal size distribution, are made for several different vertical distributions shown in Figure 2-6. These distributions are the 1968 Elterman, the 1964 Elterman (the standard in all the comparisons in these theoretical studies), and the 1964 Elterman distribution modified with single peaks located at different altitudes.

The calculated radiances, shown in Figure 2-7, confirm that they are essentially independent of the vertical distribution except in the case of a strong 5 km peak [(d) and (e) in Figure 2-6]. These peaks are 150 and 75 times greater than the normal concentration at 5 km, and would probably not occur in the real atmosphere.

2.2 Comparison of Theory and Landsat 1 Data

On the basis of the calculations discussed in the preceding sections, we find that the Landsat 1 MSS6 radiance agrees closely with

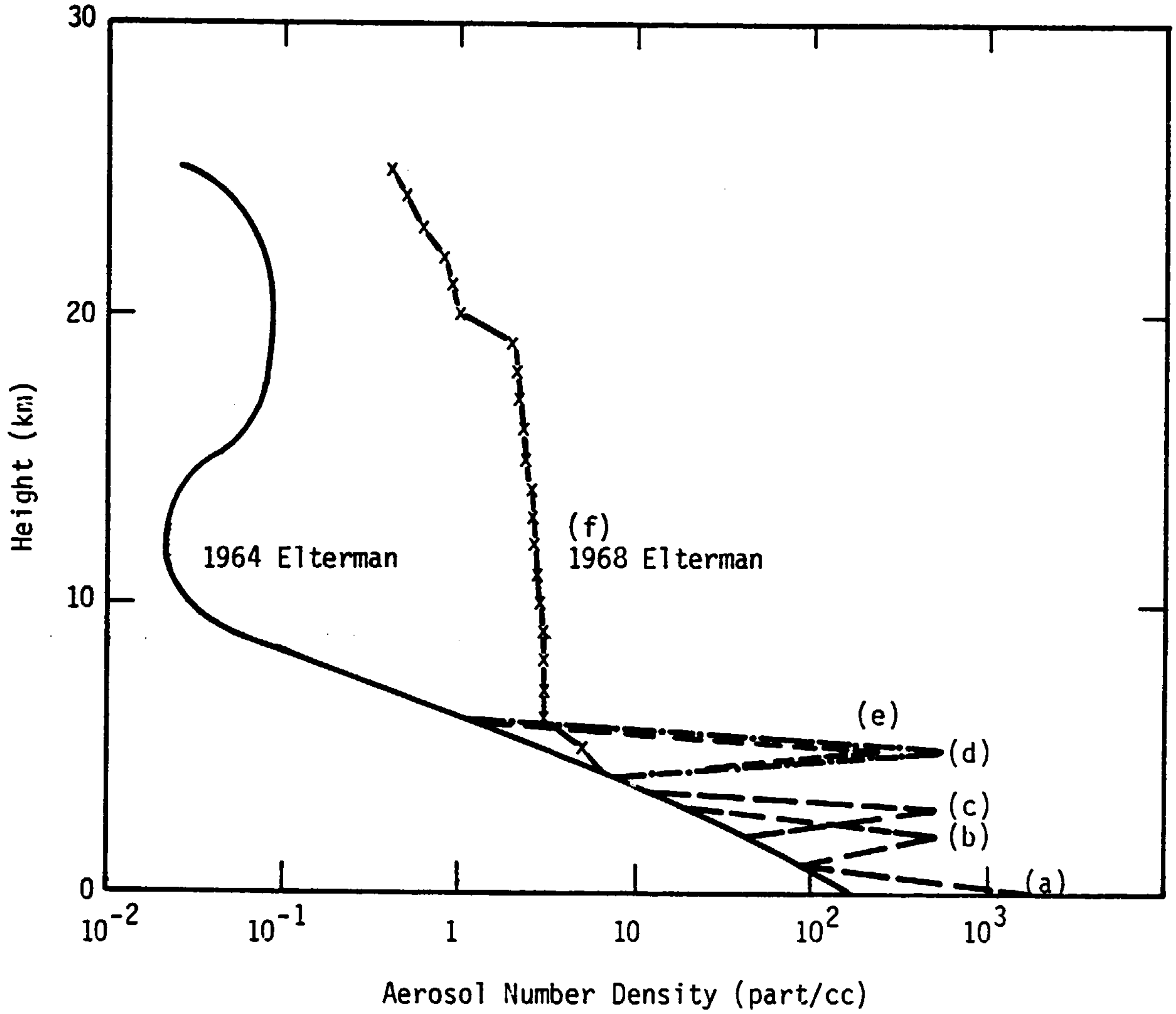


Figure 2-6. Vertical Aerosol Distributions Used in Calculations.

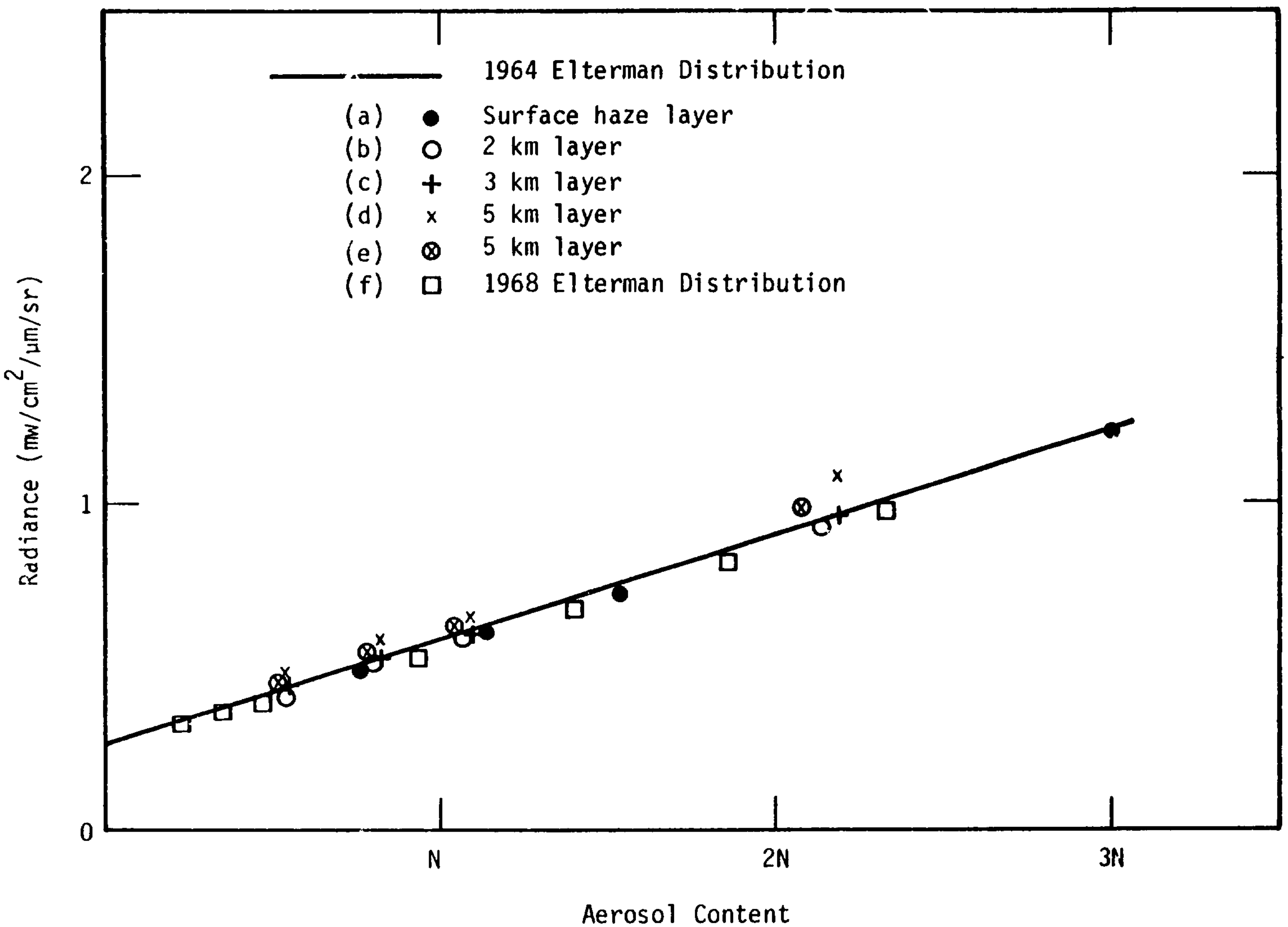


Figure 2-7. MSS6 Radiance Versus Aerosol Content for Log-Normal Size Distribution.

calculated values, assuming $\nu = 4$ and $n = 1.5 - 0i$. Hence these parameters are assumed in calculations of the radiance for the other MSS bands.

The relationships calculated for all MSS bands are shown in Figure 1-1 in comparison with the measured Landsat 1 relationships. It should be noted that the calculations are for a sun angle of 63.26° ($\cos \Theta = .45$), and that the Landsat data are normalized to this sun angle based on the theoretical variation of radiance with sun angle.[11] (It should also be noted that the measured MSS7 data in Figure 1-1 have been revised since our previous study; a re-examination of our data reduction procedures showed that an incorrect spectral bandpass was used for MSS7.) The measured and calculated data were made to agree at $N = 0$ (i.e., a pure Rayleigh atmosphere) by choosing the appropriate albedo (A) in the theoretical calculations. The values of $A = 0$, $A = 0$, and $A = 0.005$ for MSS7, 6 and 5 respectively, look reasonable on the basis of published estimates of A.[22] However, the value of $A = 0.06$ for MSS4 appears high by a factor of 4 (compared to clear water). This may be partly due to suspended matter in the water, but is probably due to a systematic error in the calibration of MSS4. The Landsat 2 data, discussed later in Section 4, show lower radiances in MSS4, with an equivalent $A = .028$; this strongly suggests that the Landsat 1 calibration is the cause of the higher Landsat 1 MSS4 radiances.

2.2.1 Water Vapor Effects in MSS7

Figure 1-1 shows that most of the measured radiances for MSS7 are lower than predicted by theory. This is expected since there is significant absorption by water vapor in this bandpass, which is not accounted for in the Dave program.

Pitts et al.[24] calculated the atmospheric transmission for the MSS7 channel as a function of water vapor content. Their results, based on high spectral resolution calculations, are shown in Figure 2-8,

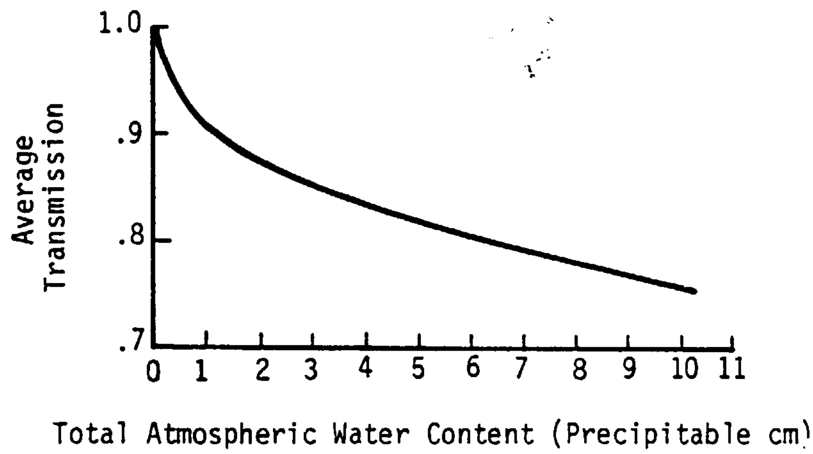


Figure 2-8. Calculated Transmission of Water Vapor in the MSS7 Band.

and agree well with band model calculations by Marggraf and Griggs.[25] The upwelling radiation traverses approximately ($1 + \sec \Theta$) airmasses where Θ is the sun zenith angle. Hence for the sun angle of 63.26° ($\cos \Theta$ = .45), to which the radiance-aerosol content relationship is normalized, the radiation traverses 3.2 airmasses. The Gutnick model water vapor distribution has a vertical water vapor content of 1.7 cm, so that the radiation traverses 5.5 cm with a transmission of 0.81, according to Figure 2-8.

Of course, the actual water vapor content at the time of Landsat data will deviate from the Gutnick model values. For typical water vapor contents we might assume, from Figure 2-8, that the transmission factor to be applied to the MSS7 data is 0.85 ± 0.1. However, since the present investigation is basically empirical, and the range of transmission values is small, it is not considered necessary to adjust the MSS7 radiance data for water vapor effects.

2.2.2 Oxygen Absorption in MSS6

The MSS6 bandpass includes the 0.76 μm oxygen band so that the MSS6 radiance will be reduced from that computed by the Dave program which neglects oxygen absorption. Based on the oxygen absorption data of Saiedy et al.[26] the absorption by oxygen in the MSS6 channel is about 5% for 3.2 airmasses. Since the oxygen concentration in the atmosphere is essentially constant, its absorption has no significant effect on the present investigation.

2.3 Contrast Measurements in Urban Areas

Our previous Landsat 1 study demonstrated that the radiance over a desert surface (high albedo ~ 0.3) is not sensitive to aerosol changes, and that the contrast of the water/desert target varies only because of aerosol effects on the radiance over the water surface (low albedo ~ 0). Hence the contrast measurement does not provide any additional information

on aerosols beyond the water radiance measurements. It was suggested, since urban areas have a lower albedo (.15 - .20) than the desert, that aerosol information might be obtained from radiance and contrast measurements over urban areas. The use of urban areas has been investigated in the present study both theoretically and with Landsat data. The results of this study are presented in Section 4.4.

2.4 Surface Radiance Measurements

Measurements of the surface radiance in the MSS bandpasses were planned to provide the inherent contrast needed for interpretation of the apparent contrast determined from the Landsat data. In addition, it was hoped that measurements of the spectral variation of the ocean radiance might provide information leading to the elimination of sun glitter effects, should they occur. This approach was not successful and, as discussed in Section 4.5, the data were not required for this investigation.

2.5 Test Sites

The test sites used in this investigation are listed in Table 2-1. The San Diego and Salton Sea sites were also used in the previous Landsat 1 study, and as before the ground truth measurements of aerosol content were made by SAI personnel using a Volz sun photometer. The NOAA-EPA sites are part of the turbidity network, which uses Volz sun photometers, operated by NOAA-EPA; these sites were selected, in a separate NOAA study[27], on the basis of their proximity to bodies of water. The LACIE (Large Area Crop Inventory Experiment) sites are operated by NASA - Johnson Space Center during the spring and summer, and utilize radiometers similar to the Volz sun photometer. The few sites used in this study were identified as being close to lakes and rivers.

The ocean sites (San Diego, Miami, Barrow, Kadena AB, and Anderson AB) were to be intercompared to see how the linear relationships varied with location. The remaining sites, all inland, were to be investigated to determine how water pollution and surrounding higher albedo land might affect the utility of inland sites for measuring the aerosol content.

Table 2-1. Test Sites.

SAI Sites		
San Diego, California	32° 45'N	117° 10'W
Salton Sea, California	33° 20'N	115° 50'W
NOAA - EPA Sites		
Miami, Florida	25° 44'N	80° 10'W
Atlantic City, New Jersey	39° 27'N	74° 34'W
Kadena AB, Okinawa	26° 21'N	127° 46'E
Anderson AB, Guam	13° 34'N	144° 55'E
Adrigole, Ireland	51° 24'N	9° 27'W
Barrow, Alaska	71° 20'N	156° 37'W
Grand Prairie, Texas	32° 42'N	97° 01'W
LACIE Sites		
Burke Co., N. Dakota	48° 53'N	102° 10'W
Divide Co., N. Dakota	48° 53'N	103° 11'W
Toole Co., Montana	48° 53'N	111° 47'W
Hill Co., Montana	48° 42'N	109° 55'W

3. DATA ANALYSIS METHODS

The techniques for analyzing the Landsat digital data and the Volz photometer data are the same as used in the Landsat 1 program.(11) In this present study, an attempt was made to measure the surface radiance of the water using an Exotech radiometer mounted in a low-flying aircraft at the San Diego and Salton Sea sites.

3.1 Landsat Data

The data for the four MSS channels have been received as bulk processed black and white 9.5 inch positive prints, and as bulk processed digital 9-track computer compatible tapes, selectively ordered after viewing the black and white products.

To extract the radiance data from the computer compatible tapes (CCT), a program was written to read data in prescribed geographical areas from the tapes on a DEC-10 computer. The areas of interest for analysis were chosen by viewing the black and white products, and selecting areas within the test sites free of obvious clouds, or effluents in the water. The voltage counts are printed out for each area, and can be converted to radiance (mw/cm^2/μm/sr) using the calibration data given in Table 3-1. It should be noted that these relationships are slightly different for tapes generated at the EROS Data Center prior to July 16, 1975. The Landsat 2 data for MSS7 could not be used in this study due to NASA procedures for producing the CCT's, as discussed in Section 4.2.

Table 3-1. Landsat 2 Radiance (R) - Voltage (V) Relationships.

MSS4	R = .8 + .2008 V
MSS5	R = .6 + .1339 V
MSS6	R = .6 + .1150 V
MSS7	R = .61 + .3360 V

The radiance values reported in Section 4 are mean values determined by averaging over an area whose size varies with the site. For large bodies of water, such as the ocean at San Diego, Miami and Adrigole, the area covers 40 pixels, but at inland sites the bodies of water are smaller, and the number of pixels have to be reduced accordingly. For inland sites the areas range from 40 pixels for the Salton Sea to 6 pixels for the lake at the Toole site.

3.2 Volz Data

The Volz data at the San Diego and Salton Sea sites were taken by SAI personnel using the same photometer as used in the Landsat 1 study. Checks on its calibration showed excellent agreement with calibrations made in recent years, indicating that no deterioration of the instrument had occurred. Data for the other sites were obtained with Volz photometers in the EPA-NOAA turbidity network, and with similar photometers at the LACIE sites.

3.3 Aircraft Data

An Exotech Model 100 radiometer, which has four channels with approximately the same spectral response as the MSS channels, was mounted in a Cessna 172 to make surface radiance measurements from low altitudes. The aircraft measurements were planned to assist the contrast investigation, and to investigate the spectral variation of the ocean radiance with view to eliminating glitter effects should they occur.

4. RESULTS

Significant results were obtained in this investigation; a large set of ocean data at San Diego showed that excellent linear relationships exist between the MSS radiances and the aerosol content of the atmosphere. Two data points at another ocean site (Adrigole) showed excellent agreement with the San Diego results, whereas a large set of ocean data at Miami exhibited a different linear relationship. The inland sites were found to be not useful for measuring the aerosol content due mostly to water pollution rather than to the higher albedo of the surrounding land. Analysis of data for San Diego showed that neither radiance nor contrast measurements are useful for determining the aerosol content in urban areas.

The measured aerosol contents and MSS radiances for the various sites are given in Tables 4-1 and 4-2.

4.1 Volz Data

Volz measurements at the time of Landsat overpasses were made, weather permitting, consistently during this program only at San Diego, and were made by SAI personnel, who also intermittently travelled to the Salton Sea site to make measurements.

The seven NOAA-EPA sites were chosen as a result of our NOAA study,[27] and arrangements were made with Mr. E. Flowers of NOAA for personnel at these sites to make special measurements at the time of Landsat overpasses. Data were acquired at these sites for the period March to September 1976. Analysis of these data showed that two sites were unsuitable: Barrow because the water near the site was always frozen, and Grand Prarie due to sediment and algae in the water. A second data acquisition period was subsequently arranged for the other five sites covering the period March to September 1977.

As part of the LACIE (Large Area Crop Inventory Experiment) program, operated by NASA-JSC, the aerosol content is measured routinely

Table 4-1. Landsat 2 Data.

Date	cos Sun Zenith	Volz	Normalized MSS Radiance MSS4	MSS5	MSS6	MSS7
San Diego (Ocean)						
03-30-75	.73	.71N	2.59	1.38	.75	.50+
05-05-75	.84	1.10N	3.03	1.59	1.12	.86
07-16-75	.85	1.31N	3.16	1.74	1.18	.71
08-21-75	.80	1.19N	3.13	1.67	1.07	.61*
09-26-75	.71	1.35N	3.19	1.74	1.08	.60*
10-14-75	.64	.64N	2.53	1.26	.74	.55+
11-01-75	.57	.53N	2.50	1.20	.71	.58+
11-19-75	.50	.46N	2.39	1.20	.69*	.60+
12-25-75	.42	.74N	2.50	1.35	.82	.60+
04-11-76	.78	1.07N	3.11	1.61	.97	.56*
04-29-76	.82	1.34N	3.03	1.62	1.11	.73
06-22-76	.86	.92N	2.39	1.36	.82	.50+
10-08-76	.66	.56N	2.44	1.19	.69	.54+
10-26-76	.59	1.48N	3.10	1.76	1.07	.61*
12-01-76	.45	.29N	2.02	1.13	.62*	.61+
01-24-77	.44	.57N	2.31	1.14	.65*	.61+
02-11-77	.50	.56N	2.33	1.18	.69*	.60+
03-01-77 (La Jolla)	.57	.68N	2.83	1.66	1.05	.59*
03-01-77 (70 km west of La Jolla)			2.61	1.41	.88	.60*
03-19-77	.66	1.17N	3.02	1.64	.98	.57*
04-24-77	.79	1.04N	2.84	1.42	.86	.52*
07-05-77	.82	.81N	2.43	1.25	.73	.46+
09-15-77	.70	.96N	2.75	1.41	.84	.52+

Table 4-1. Landsat 2 Data (continued).

Date	cos Sun Zenith	Volz	Normalized MSS Radiance			
			MSS4	MSS5	MSS6	MSS7
Salton Sea (50 km x 15 km)						
06-09-75	.87	1.41N	3.20	1.81	1.19	.65
06-27-75	.87	.82N	2.43	1.35	.78	.43*
10-31-75	.57	.54N	2.69	1.61	.98	.58+
11-18-75	.52	1.11N	3.14	1.99	1.25	.73*
12-06-75	.45	.54N	2.61	1.50	.88	.61+
03-23-76	.69	.77N	2.58	1.70	.96	.51+
04-10-76	.77	1.13N	3.25	1.97	1.33	.74
05-16-76	.85	.95N	2.63	1.59	.99	.55*
06-03-76	.86	1.31N	2.91	1.66	.98	.48*
05-29-77	.83	.99N	2.59	1.44	.83	.49*
06-16-77	.83	.72N	2.53	1.48	.88	.46*
07-22-77	.80	1.02N	2.77	1.59	.90	.47*
Miami (Ocean)						
04-02-76	.77	1.47N	--	--	1.03	.55*
04-20-76	.82	1.31N	--	--	.96	.59*
06-30-76	.90	1.60N	--	--	.94	.46*
08-05-76	.88	1.73N	--	--	1.02	.60*
04-15-77	.78	1.62N	--	--	1.17	.60*
05-20-77	.82	2.37N	--	--	1.20	.56*
06-25-77	.81	2.89N	--	--	1.35	.81
06-26-77	.81	2.82N	--	--	1.47	1.07
08-01-77	.79	1.45N	--	--	1.08	.51*
08-18-77	.77	1.66N	--	--	.83	.49+
08-19-77	.77	1.68N	--	--	1.01	.56*
09-05-77	.74	.65N	--	--	.89	.49+

Table 4-1. Landsat 2 Data (continued).

Date	cos Sun Zenith	Volz	Normalized MSS Radiance MSS4	MSS5	MSS6	MSS7
Adrigole (Ocean)						
04-12-76	.66	.76N	2.68	1.29	.75	.54$^+$
06-01-77	.79	1.21N	2.82	1.58	1.02	.69*
Barrow (Ocean)						
07-18-76	.73	.51N	3.16	1.66	.90	.56$^+$
08-06-76	.56	.22N	3.04	1.43	.70	.59$^+$
Atlantic City (Reservoir, 300 meters x 2000 meters)						
04-18-76	.77	3.38N	4.33	2.55	1.82	1.17
04-19-76	.78	2.89N	4.66	2.74	1.89	1.47
06-12-76	.91	2.35N	3.07	1.82	1.45	1.00
07-18-76	.88	1.79N	2.71	1.59	1.14	.83
08-22-76	.83	2.96N	4.26	2.48	1.97	1.36
08-23-76	.82	2.90N	4.19	2.48	2.05	1.42
09-28-76	.64	.77N	2.79	1.58	1.07	.68*
Burke County (River, 500 meters wide)						
05-28-76	.82	.58N	2.69	1.64	1.12	.59*
05-28-76 (cloud shadow on land)			2.05	1.31	.94	.57*
07-21-76	.79	.95N	3.11	1.82	1.62	.99
10-01-76	.53	.72N	3.09	1.97	1.38	.63*
06-28-77	.80	.38N	3.24	1.86	1.60	.63*
06-28-77 (cloud shadow on river)			2.33	1.25	1.01	.46$^+$

Table 4-1. Landsat 2 Data (continued).

Date	cos Sun Zenith	Volz	Normalized MSS Radiance MSS4	MSS5	MSS6	MSS7
Divide County (Lake, 2000 meters x 500 meters)						
08-09-76	.74	.30N	2.81	1.82	1.14	.49^{+}
09-14-76	.62	.30N	2.64	1.67	.94	.56^{+}
Hill County (River, 1000 meters wide)						
05-16-76	.80	.62N	2.93	1.71	1.05	.63*
06-03-76	.82	.48N	3.35	1.90	1.19	.73
09-19-76	.59	.48N	3.77	1.89	.82	.57^{+}
10-07-76	.50	.53N	4.03	2.21	.93	.59^{+}
08-08-77	.73	.72N	4.11	2.07	1.12	.56*
Toole County (Lake, 500 meters x 500 meters)						
06-04-76	.82	.72N	2.56	1.64	1.20	.71
07-10-76	.81	.44N	2.28	1.27	.78	.59*
07-28-76	.78	.44N	2.03	1.23	.82	.47^{+}
09-20-76	.59	.30N	2.32	1.36	.86	.57^{+}
04-23-77	.71	.11N	2.78	1.77	1.11	.72*
05-11-77	.77	.06N	2.46	1.51	.99	.48^{+}
07-22-77	.77	.22N	2.25	1.27	.90	.47^{+}

* Count < 0

$^{+}$ Count = 0

Table 4-2. Landsat 1 Data.

Date	cos Sun Zenith	Volz	Normalized MSS Radiance MSS4	MSS5	MSS6	MSS7
San Diego (Ocean)						
10-23-75	.59	.95N	3.71	1.59	.92	.56
12-16-75	.41	.38N	2.48	.74	.38	.08*
04-20-76	.74	1.27N	3.39	1.43	.75	.33
05-08-76	.79	1.06N	3.34	1.37	.74	.41
Miami (Ocean)						
01-09-73	.55	1.57N	--	--	1.03	.45
04-09-73	.82	1.84N	--	--	1.12	.77
08-21-75	.79	1.35N	--	--	1.06	.63
09-08-75	.77	1.39N	--	--	.97	.57
Atlantic City (Reservoir, 300 meters x 2000 meters)						
08-19-75	.75	1.55N	3.15	1.54	.94	.64
Grand Prairie (Lake, 4.5 km x 3 km)						
10-09-75	.64	1.56N	5.53	3.50	1.69	.72

* Count < 1.0

at twenty-nine sites, during the crop growing season, at the time of Landsat overpasses. The four sites used in our investigation are near rivers or lakes, and the data measured at them for the period March to September 1976 and 1977, were obtained from Dr. D. Pitts at NASA-JSC.

It is seen in Tables 4-1 and 4-2 that two of the NOAA-EPA sites, Kadena AB and Anderson AB produced no data, and that Atlantic City produced none in the 1977 period. Apparently this was due to problems in maintaining the turbidity network; when instruments failed there were no replacements for them. In addition, there is some question concerning the reliability of the instruments in operation, since they have thermopile detectors and require frequent calibration, which was not available due to man-power problems. It should be noted that the Volz instrument used at San Diego and the Salton Sea has a silicon detector, and has shown a remarkably constant calibration for several years. The data obtained at the LACIE sites are believed to be reliable, although no Divide data were obtained in 1977 due to instrument failure.

4.2 Landsat 2 Data

The MSS radiances determined from the Landsat 2 digital tapes, and the calibration data in Table 3-1, are given in Table 4-1. These values are normalized to a sun angle of $\mu = 0.45$ to account for the different sun angles, based on the theoretical variation of radiance with sun angle determined in the previous Landsat 1 study.[11] No radiances for MSS4 and 5 for the Miami site are shown, as these values are influenced by bottom reflection since the water is shallow in the vicinity of the site. The radiances for MSS7 shown in Table 4-1 are not useful for this investigation due to the calibration procedures used in producing the CCT's, as discussed below.

It is seen in Table 3-1 that the calibration data for the Landsat 2 MSS channels are quite different from those for Landsat 1, in that there is an offset at zero count, i.e., at zero count the radiance has a

small but significant value. This results from the necessity, at the NASA data processing center, to normalize the output of the six detectors per MSS channel to avoid striping in the black and white prints.

Since the CCT's do not permit negative count values, the current system does not allow for measured radiances below 0.6 mw/cm^2/µm/sr. Thus, the low radiance values, particularly in MSS6 and 7, of concern to this investigation can be incorrect. It is seen in the data presented in Table 4-1 that most of the MSS7 counts were 0 or 1, and that the anticipated linear radiance-aerosol content relationship is not found for MSS7 (see Figure 4-3). In order to evaluate the effect of these corrected procedures, five raw data tapes were obtained from NASA-GSFC. The raw tapes contain the uncorrected data, and hence contain the low radiance information.

4.2.1 Discussion of Raw Data Tapes

The relationships between the radiance and the voltage counts for the raw and calibrated data are given by

$$V_u = \alpha + \beta \frac{(R - R_{min})}{(R_{max} - R_{min})} \tag{4-1}$$

$$\begin{aligned} V_c &= 128 \frac{(R - R_{min})}{(R_{max} - R_{min})} \quad \text{for MSS4, 5, 6} \\ V_c &= 64 \frac{(R - R_{min})}{(R_{max} - R_{min})} \quad \text{for MSS7} \quad . \end{aligned} \tag{4-2}$$

Hence, we have

$$\begin{aligned} V_c &= \frac{128}{\beta} (V_u - \alpha) \text{ for MSS4, 5, 6} \\ V_c &= \frac{64}{\beta} (V_u - \alpha) \text{ for MSS7} \end{aligned} \tag{4-3}$$

where

V_u is the uncalibrated digital voltage

V_c is the calibrated digital voltage

R_{max} is the specified maximum radiance

R_{min} is the specified minimum radiance

R is the measured radiance

α is the detector offset

β is the detector gain.

From Eq. (4-3) it can be seen that if $V_u < \alpha$ then V_c is negative. When this occurs V_c is assigned the value zero, i.e., all negative values of V_c are assigned the value zero, and radiance information is lost at low radiance values.

In order to analyze the raw data tapes our processing technique was reprogrammed to print out the calibration data, which include α and β, at the end of each scan line. These values, which are different for each of the 24 detectors (6 per MSS channel), are used with Eq. (4-1) to compute the raw radiance for each pixel.

The comparison of the radiances determined from the raw and calibrated tapes for five overpasses are given in Table 4-3. These data show that the MSS4, 5, and 6 radiances are not significantly affected by the processing, but that the MSS7 radiances are clearly affected. The radiance values in Table 4-3 have been normalized to $\mu = 0.45$, and plotted against aerosol content in Figure 4-1. It is seen that by considering the raw radiance values the MSS7 radiance-aerosol content relationship is in closer agreement to the Landsat 1 relationship. Hence it is assumed that discrepancies between the Landsat 1 and Landsat 2 MSS7 relationship would be eliminated by use of the raw data tapes. However, it was not possible, within the scope of this program, to analyze raw tapes for all overpasses.

It should be noted that some problems were encountered due to differences in the registration in four of the five sets of corrected and raw tapes, i.e., a given geographical feature was located a different number of scan lines from the start of each tape of a particular scene.

Table 4-3. Comparison of Corrected and Raw Data Tapes.

		Radiances ($mw/cm^2/\mu m/sr$)	
Date	Channel	Corrected	Raw
03-30-75	MSS4	3.16 (3.27)*	3.14
	MSS5	1.68 (1.43)	1.65
	MSS6	.92 (.72)	.90
	MSS7	.61 (.87)	.43
05-05-75	MSS4	4.21	4.25
	MSS5	2.21	2.26
	MSS6	1.55	1.60
	MSS7	1.19	1.07
10-31-75	MSS4	2.83	2.80
	MSS5	1.70	1.69
	MSS6	1.03	.96
	MSS7	.61	.40
11-18-75	MSS4	3.17	3.11
	MSS5	2.01	2.00
	MSS6	1.27	1.26
	MSS7	.74	.73
12-06-75	MSS4	2.61	2.60
	MSS5	1.50	1.52
	MSS6	.38	.90
	MSS7	.61	.22

* The parenthetical values were obtained from an EROS corrected tape, supposedly identical to the other tape from GSFC.

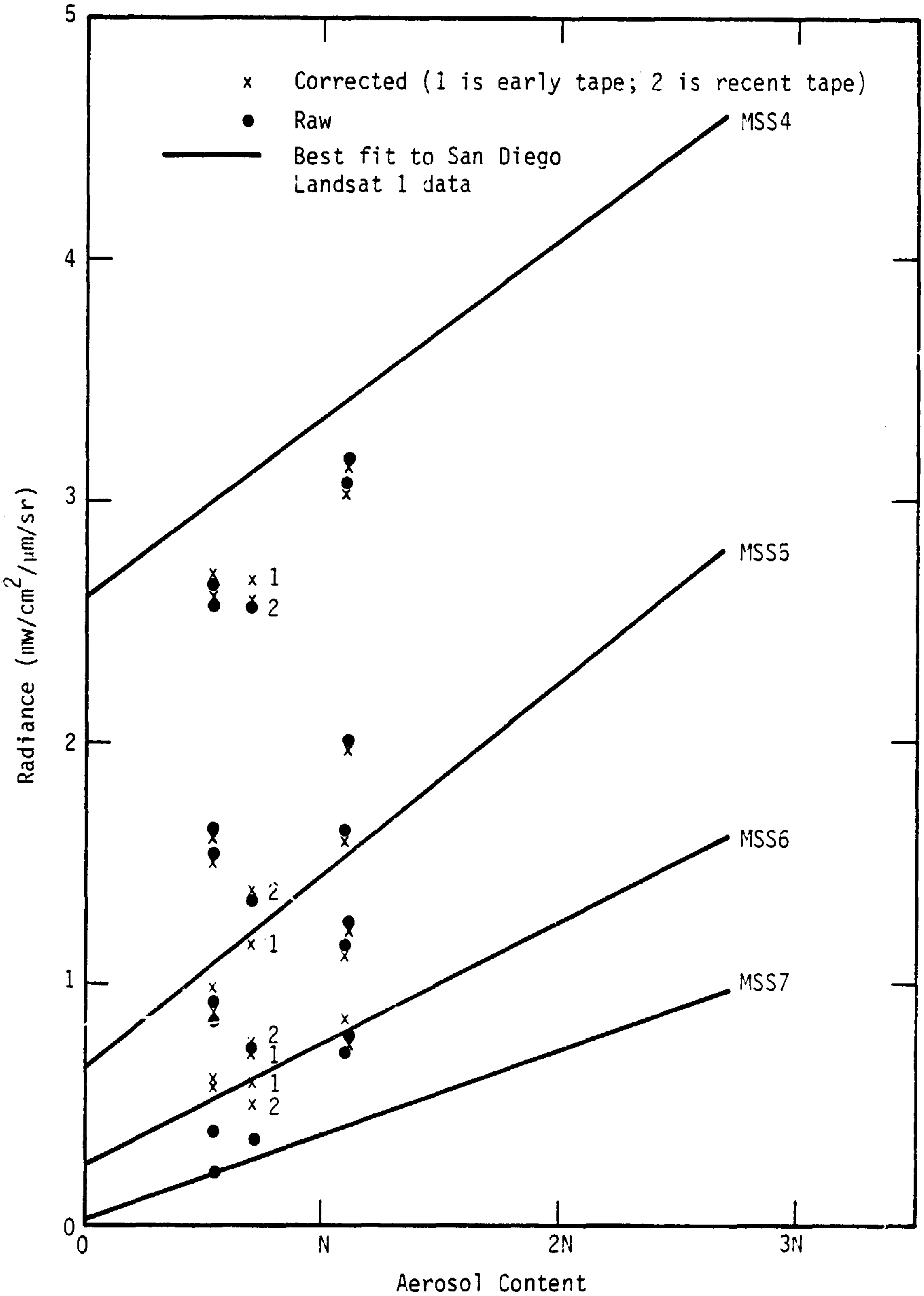


Figure 4-1. Comparison of Raw and Corrected Data.

Another point to be noted is the differences (see Table 4-3) found between two corrected tapes for March 30, 1975. The first tape from EROS was suspect when first analyzed since it showed the MSS6 radiance to be less than the MSS7 radiance, which was not observed for any other tape. The later tape from NASA-GSFC gives more reasonable radiance values, suggesting that the EROS tape was in error. It is assumed that this is an isolated error, but the possibility exists that other data points could have similar errors.

4.3 Landsat 2 Radiance-Aerosol Content Relationships

The radiance-aerosol content relationships for the various sites are presented below. The largest and most reliable set of data is that obtained at San Diego. At this site the target is unpolluted ocean water, and the aerosol content is measured with a reliable and well-calibrated Volz photometer. At the other sites there are uncertainties about either the reliability of the photometer or the suitability of the water target being used.

4.3.1 San Diego

The results for San Diego are shown in Figures 4-2 and 4-3; the solid lines are the regression lines computed for each MSS channel. The MSS7 data are given in Figure 4-3 to illustrate the problems experienced in this channel with the calibration procedures used in producing the CCT's (see Section 4.2); it is clear that no significant correlation exists, so that no further discussion of MSS7 data is presented.

The relationships appear best for MSS5 and MSS6, with MSS4 showing somewhat more scatter of points due to the fact that it is affected more by suspended matter in the water. The linear regressions and the correlation coefficients are given in Table 4-4, together with the equivalent surface albedos for each channel. The equivalent surface albedo is that surface albedo in the theoretical calculations which makes the calculated and measured radiances agree at $N = 0$ (i.e., a pure Rayleigh atmosphere).

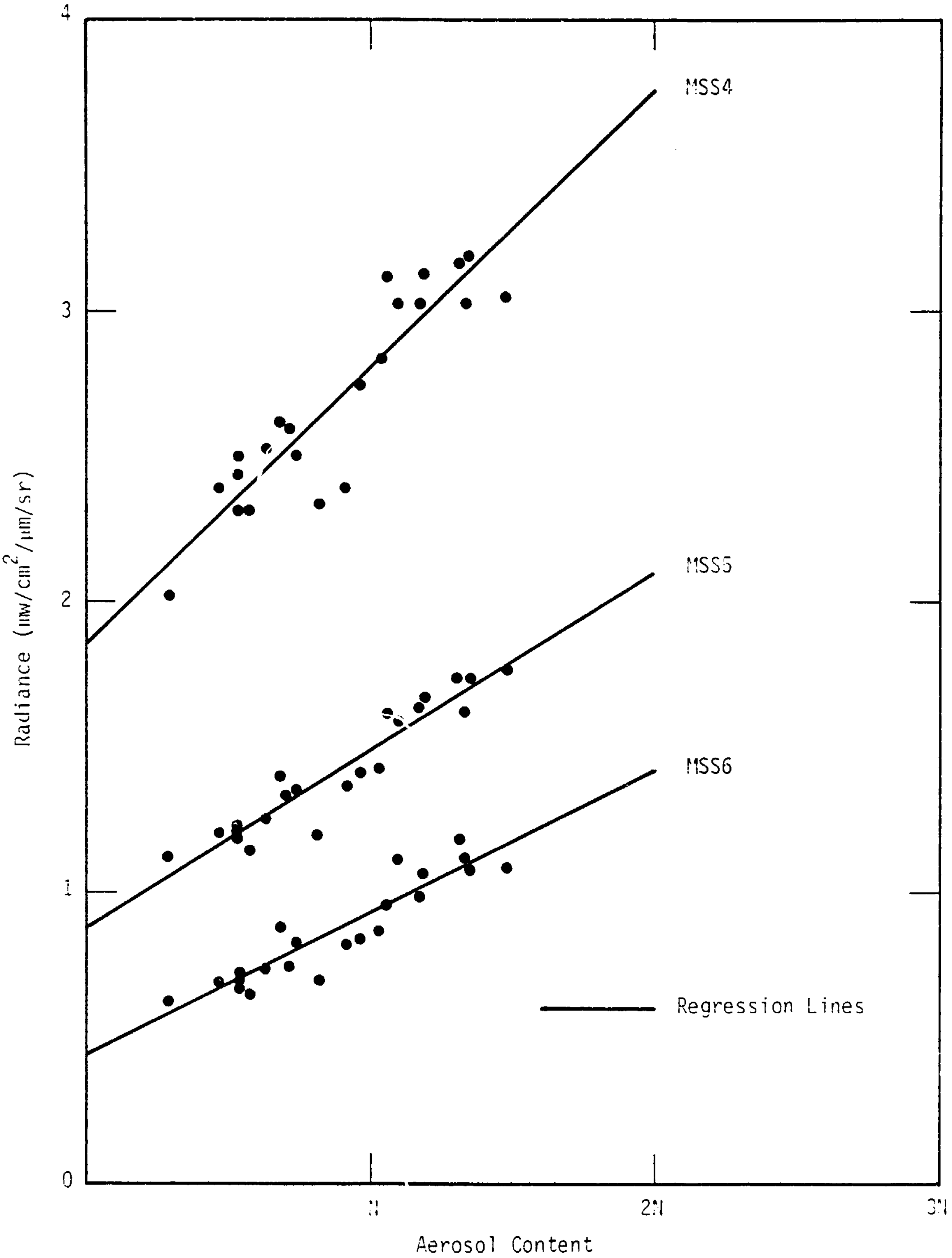


Figure 4-2. Landsat 2 Radiance Versus Aerosol Content at San Diego for MSS4, MSS5 and MSS6.

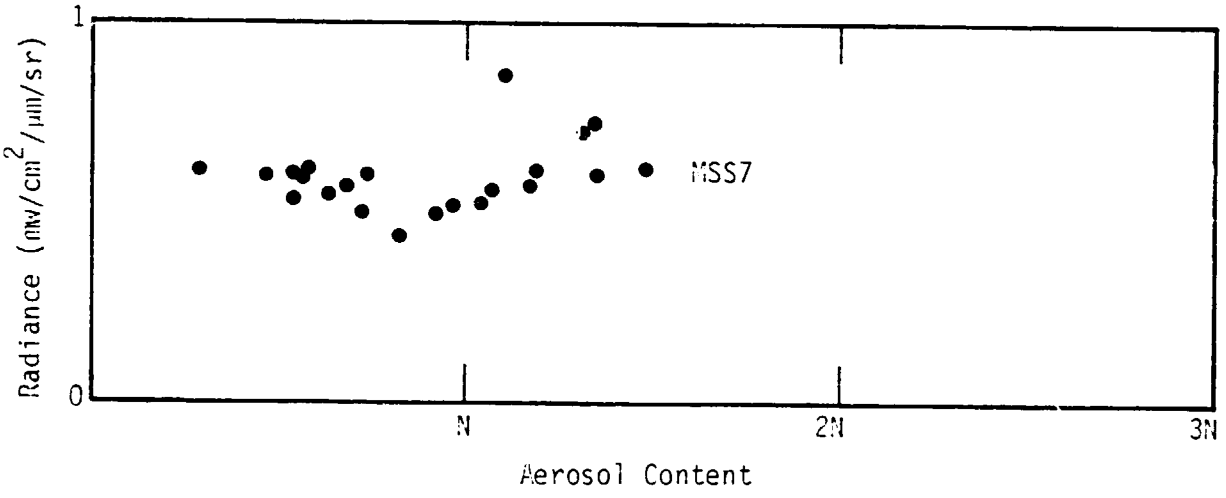


Figure 4-3. Landsat 2 Radiance Versus Aerosol Content at San Diego for MSS7.

Table 4-4. Linear Regressions, Correlation Coefficient (r), and Equivalent Albedo (A).

San Diego (22 points)

MSS4	Radiance = 1.86 + .95N	r = .85	A = .028
MSS5	Radiance = .88 + .61N	r = .90	A = .015
MSS6	Radiance = .44 + .49N	r = .86	A = .01

*Miami (12 points)

MSS6	Radiance = .64 + .25N	r = .71	A = .02

* See Section 4.3.3 for discussion on validity of Miami data.

The albedos for MSS5 and MSS6 are slightly higher than determined in the previous Landsat 1 study, but are still in good agreement with published data[22] (see Section 2.2). The albedo for MSS4 is significantly lower than that found for Landsat 1, and is in better agreement with the published data. It is also noted that the radiances for MSS4 are significantly lower for Landsat 2, whereas the MSS5 and MSS6 radiances are generally a little higher for Landsat 2 than for Landsat 1. These differences between Landsat 1 and Landsat 2 are assumed to be due to differences in the radiometric calibrations of the two satellites.

The San Diego MSS5 and MSS6 relationships show excellent agreement with the theoretical calculations for a Junge distribution ($\nu = 4.0$) and refractive index of 1.5, as shown in Figure 4-4. The comparison for MSS4 is not so good, with a higher ν value being required for better agreement. This poorer agreement in MSS4 may be due to a calibration problem, as was inferred in comparing this channel in Landsat 1 and Landsat 2, or it may be due to the fact that the radiance in this channel is more sensitive to suspended matter in the water. This value of about 4.0 for ν, is higher than generally found for the atmosphere using other optical techniques (see Section 2.1.1), but the estimated value of ν depends on the choice of refractive index n. Thus, it might be inferred from Figure 2-4 that the Landsat data might be equally well fitted by a model with the reasonable values of $\nu = 3.5$ and $n = 1.55$. It is quite possible that the aerosols typically found over the ocean at San Diego have properties different from those measured by the other methods at other locations; indeed there seems to be a difference between the Landsat data of San Diego and Miami, as discussed below in Section 4.3.3. The Miami data agrees better with a model with $n = 1.4$ and $\nu = 3$, or $n = 1.5 - 0.01i$ and $\nu = 3.0$. However, as discussed in Section 4.3.3 there are some doubts about the Miami data. Table 4-5 compares the values of n and ν estimated by this work and by the other techniques.

One of the potential problem areas, recognized since the inception of this Landsat study, was the effect of sun glitter. Sun

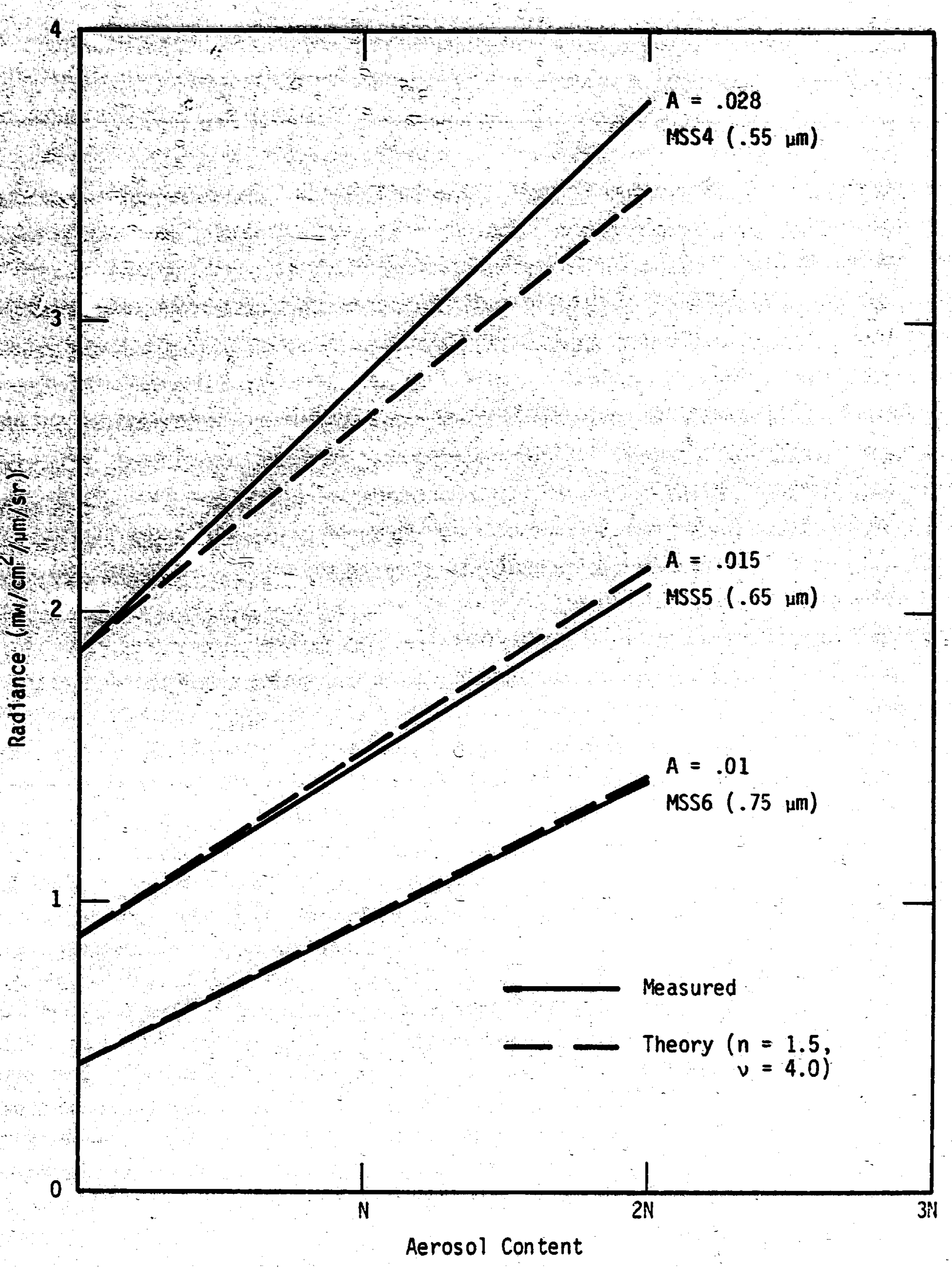


Figure 4-4. Comparison of San Diego Data and Theory.

Table 4-5. Estimates of Refractive Index and Size Distribution.

Method	Location	n	ν
Horizontal Transmission(14)	Chesapeake Bay	3.57	1.50
Solar Aureole(15)	Gainesville, Fla.	3.5	1.50 - 0.01i
Sun Photometry(16)	Tucson, Arizona	3.32	1.54
Landsat 2	San Diego, Calif.	4.0 3.5	1.50 1.55
Landsat 2	Miami, Florida	† 3.0 3.0	1.4 1.5 - 0.01i

†See Section 4.3.3 for discussion on validity of Miami data.

glitter was never clearly identified in the black and white prints received in this program. However, some evidence of sun glitter might be found in the San Diego data for March 1, 1977. This was a very windy day, with a large fraction of the ocean covered with whitecaps; it was much more windy than observed for any other overpass at San Diego. The radiances measured just off-shore from the Volz measurement at La Jolla show values higher than expected (see Table 4-1). Since the sea was rough, and the target area is in the sun's direction as seen by the MSS, higher values might be expected due to sun glitter. This La Jolla target is about 35 km east of the sub-satellite track, so a similar area about 35 km west of the sub-satellite track looking away from the sun (i.e., 70 km west of La Jolla) was examined. It was found that the radiance values were lower and in good agreement with previous results. Thus it appears that sun glitter was influencing the La Jolla radiances, although it is not absolutely certain that the wind, sea state, and aerosol content were the same 70 km west of La Jolla.

4.3.2 Salton Sea

The results for the Salton Sea are shown in Figure 4-5 in comparison with the San Diego regression lines. The ground-truth data for this site are reliable since they were obtained by SAI personnel using the same Volz photometer that was used at San Diego. However, it is noted that the radiances for five of the twelve data points seem too high. The reason for these five points showing apparently high radiance values is not clear. The conditions on these days did not appear different from other overpasses, i.e., no obvious water turbidity or sun glitter, which could produce higher radiances. The possibility that the Volz reading is in error is discounted; also, it is unlikely that the atmospheric aerosol content would vary by about 0.5N (necessary for these radiances to agree with the other data) between the Volz site on shore and the area analyzed, about 2 km off shore.

To investigate this problem further, the surface meteorological data at Imperial County Airport (60 km south of the Salton Sea) were obtained for the dates of the Salton Sea overpasses. No correlation was found between the radiances and surface humidity or temperature. It was found that higher radiances generally occurred when the wind was from the South or East. This suggests the possibility that two different types of particles, with different optical properties, might be causing the difference in radiances. However, a straight line fitted to the five high points intercepts the radiance axis at a higher radiance than the line through the other points. The intercept should be independent of the particle type since it represents the radiance due to pure Rayleigh scattering. Hence it is suspected that the five higher radiance values are due to undetected water pollution. Some Landsat overpasses show the Salton Sea to be very polluted, presumably due to irrigation run-off from Imperial Valley.

Thus, it must be concluded that a large inland body of water, which is subject to being polluted, should not be used as a target to determine the atmospheric aerosol content.

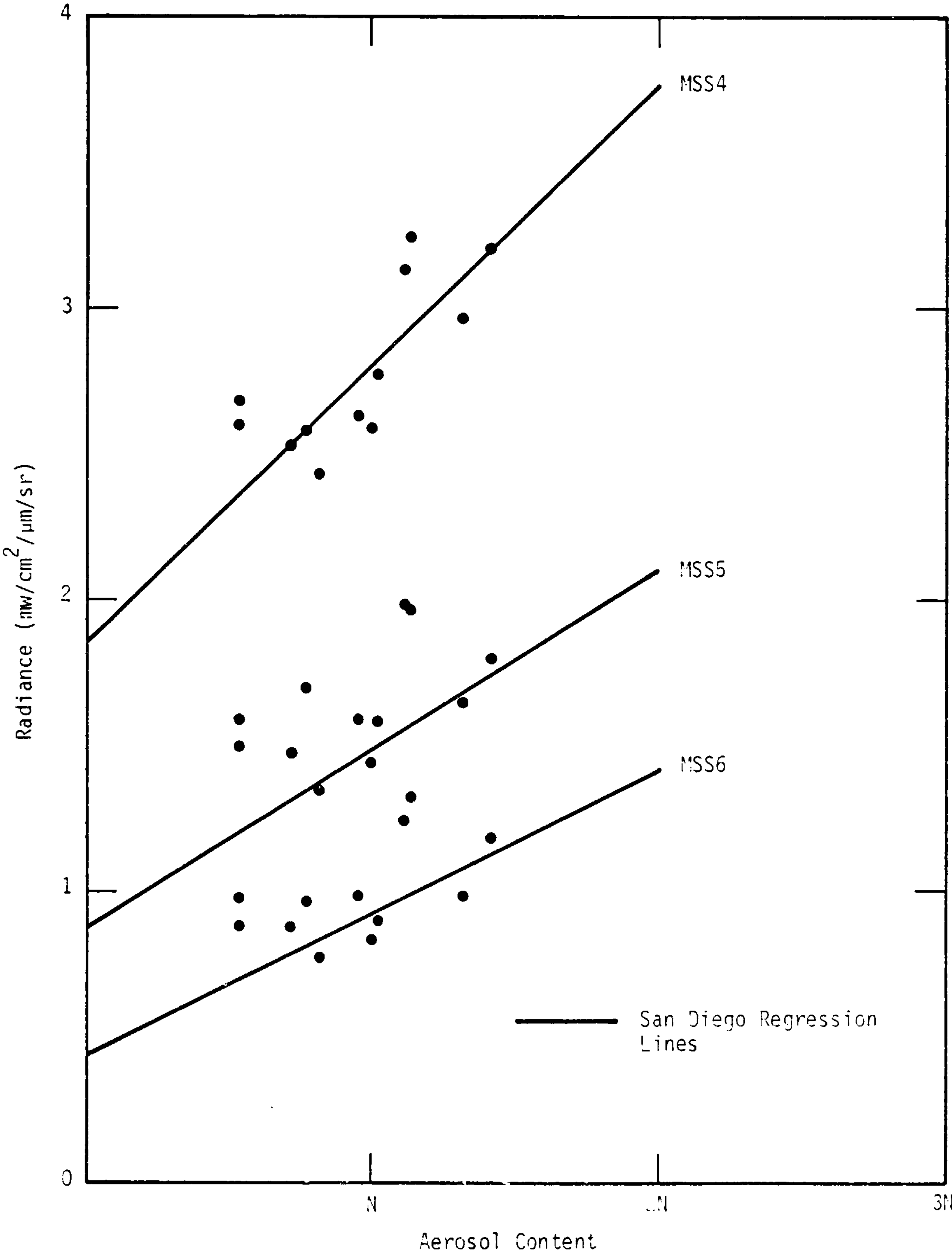


Figure 4-5. Landsat 2 Radiance Versus Aerosol Content at Salton Sea for MSS4, MSS5 and MSS6.

4.3.3 Miami

The results for Miami are shown in Figure 4-6, in comparison with the San Diego regression line. Only the MSS6 data are shown since the water at this site is shallow and the radiances for MSS4 and MSS5 are influenced by reflection from the bottom. Indeed, it is not certain that bottom reflection is not affecting the results shown for MSS6. Figure 4-6 also shows two computed regression lines for Miami; the first line is for all twelve points, whereas the second one ignores the point at 0.6N which is the only low aerosol content and shows a higher than expected radiance. The fact that these lines indicate a higher effective surface albedo than at San Diego suggests that there are some residual bottom effects causing higher radiances.

Another factor to be considered in analyzing the Miami data is the presence of Sahara dust over Miami on at least two occasions. It was noted by the observer making the Volz measurements that the 2.82N and 2.98N aerosol contents were high due to a Sahara dust haze over Miami. Since Sahara dust has more larger particles than the normal atmospheric aerosol size distribution (i.e., a smaller ν in the Junge distribution) a lower radiance might be expected. Thus if these points were for the normal Miami aerosol, the radiances would have been larger, resulting in a steeper regression line and a lower effective surface albedo. However, the other radiances (when Sahara dust was not reported) still tend to be lower than for the San Diego data, suggesting some difference in the aerosol optical properties at the two sites. The situation is not clear though since it was found (see Section 4.6 and Figure 4-14) that the earlier Landsat 1 results for Miami were not significantly different from those for San Diego.

It is apparent from the above discussion that considerably more data are required in order to determine the significance of bottom effects and changes of aerosol type.

4.3.4 Adrigole

Only two data points were obtained for Adrigole, and as shown in Figure 4-7, they show excellent agreement with the San Diego data.

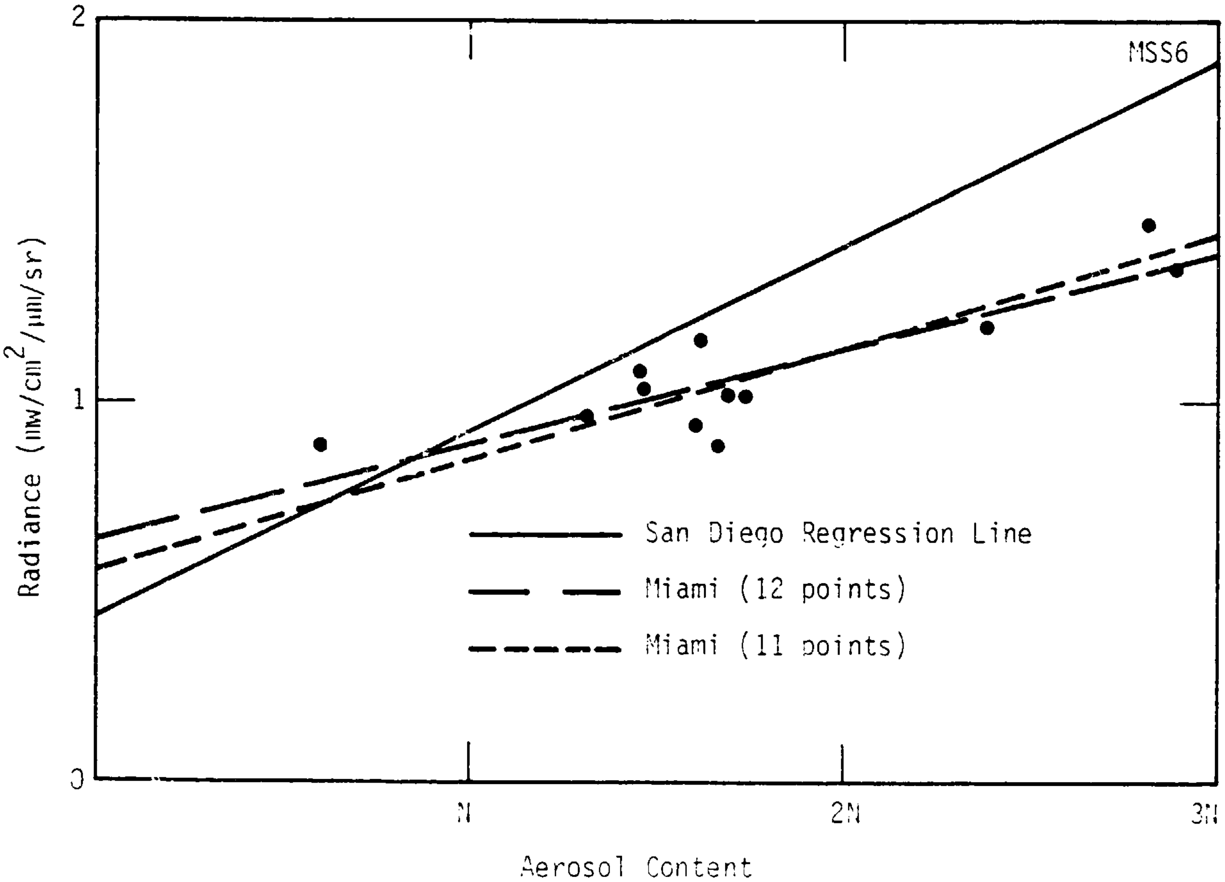


Figure 4-6. Landsat 2 Radiance Versus Aerosol Content at Miami for MSS6.

This is of great importance since the target at this site is the Atlantic Ocean, without the problems experienced at Miami, suggesting that the San Diego results have global application when the target is the open ocean and the aerosols are not unusual.

4.3.5 Atlantic City

Seven data points were obtained for this site, and, as shown in Figure 4-7, they are generally for high aerosol contents. The data show fair agreement with the San Diego data, particularly for MSS6. It is noted that the radiances for 1.71N and 2.35N tend to be low. This is surprising since the target is a reservoir (approximately 300 x 2000 m) rather than the ocean or a large body of water, and higher radiances were expected for two reaons. The first is that at all other inland sites there has been evidence of water pollution increasing the radiances. The second reason is that the small area of water is surrounded by land which has a higher reflectivity than water and should increase the observed water radiance. It is possible that the aerosols at this site are of anthropogenic origin, and perhaps have optical or size distribution properties which reduce the expected higher radiances. Much more data would be required to satisfactorily explain these results.

4.3.6 Barrow

This site was not useful in this investigation since the water by the site was always frozen, and the closest body of ice-free water was about 40 km from the Volz site. It is likely that the aerosol content over the water was different from that at the Volz site. In addition, the large areas of high-reflectivity ice near the water should cause higher radiances over the water. The two data points in Figure 4-7 show that indeed poor agreement was found with the San Diego results.

4.3.7 Burke County

The data for the LACIE sites are plotted in Figures 4-8 and 4-9. MSS5 is shown separately for clarity since there is considerable overlap

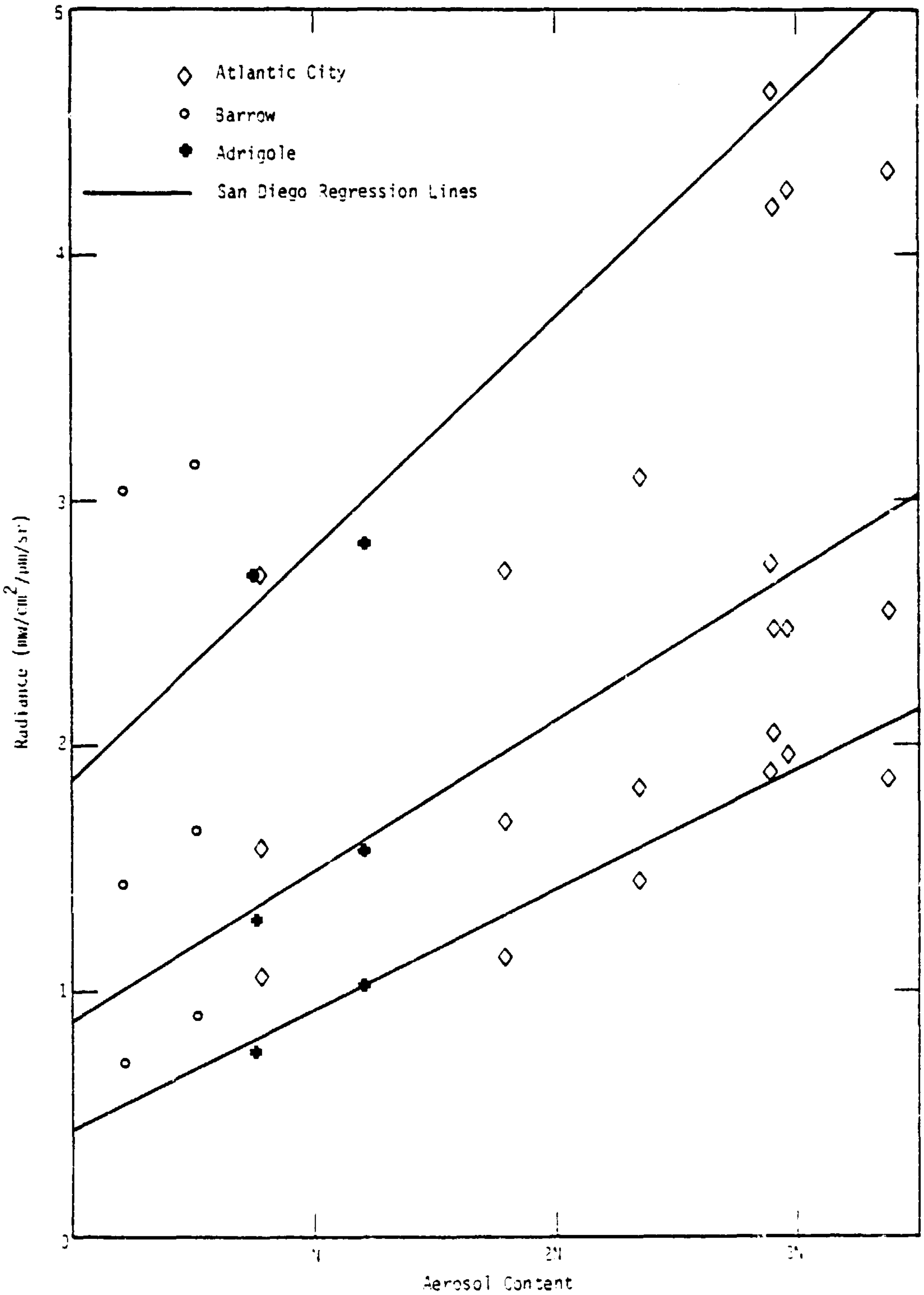


Figure 4-7. Landsat 2 Radiance Versus Aerosol Content at Atlantic City, Barrow and Adrigole for MSS4, MSS5 and MSS6.

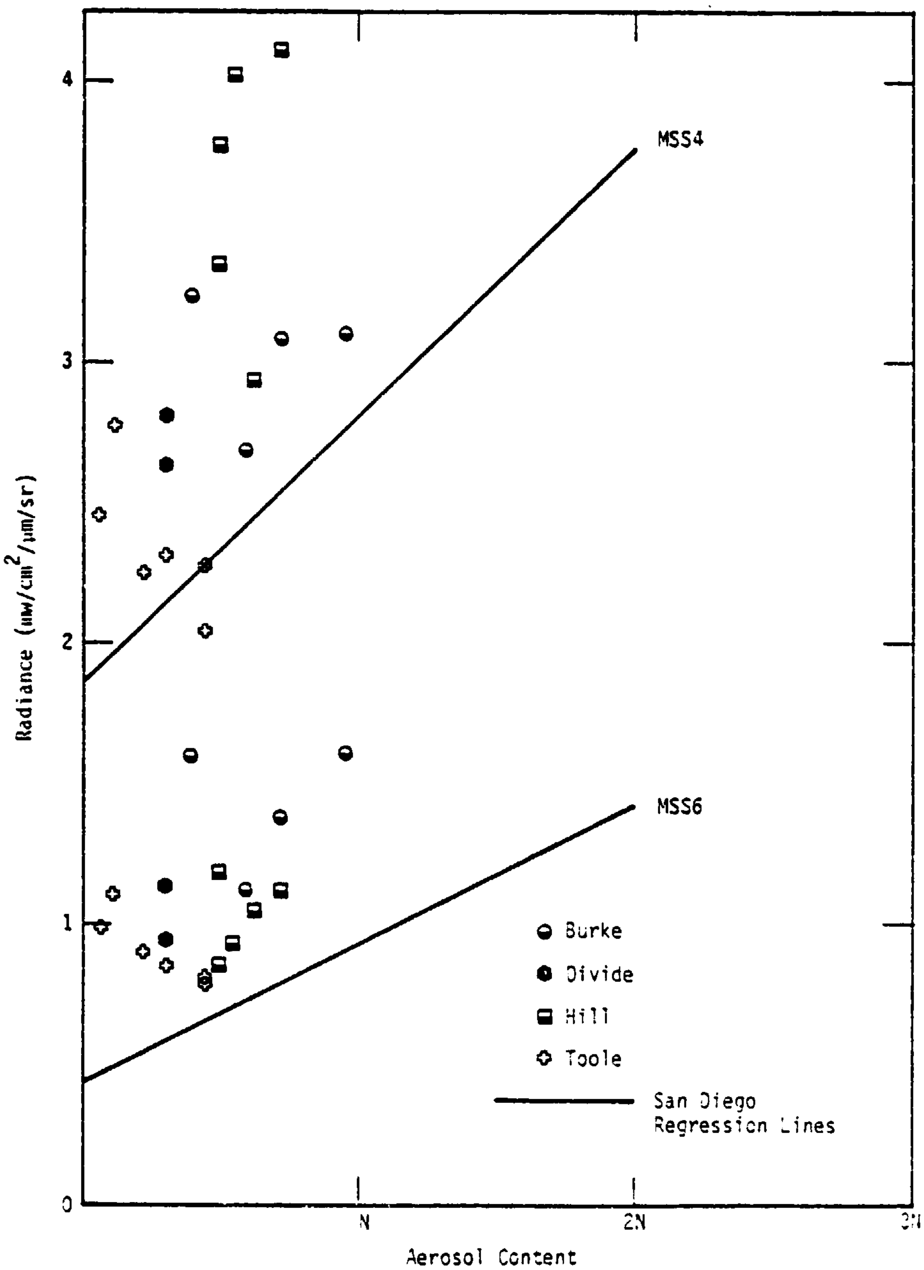


Figure 4-8. Landsat 2 Radiance Versus Aerosol Content at LACIE Sites for MSS4 and MSS6.

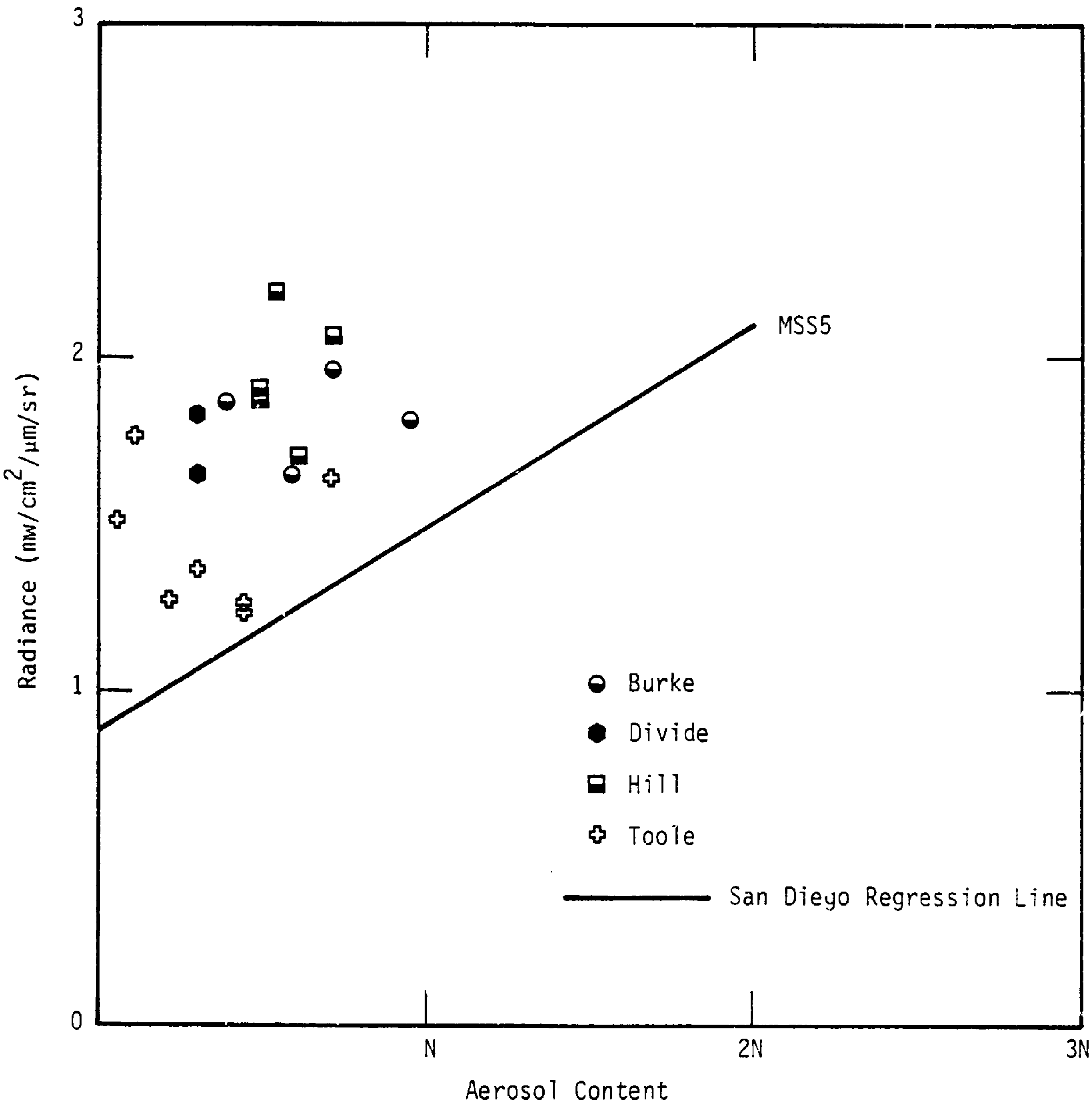


Figure 4-9. Landsat 2 Radiance Versus Aerosol Content at LACIE Sites for MSS5.

of data for the different channels. The four data points, obtained for a river about 500 meters wide and 3 km from the Volz site, show significantly higher radiances than the San Diego results. This was expected since the black and white prints clearly showed pollution in parts of the river. Of particular interest at this site are two overpasses when isolated cumulus clouds cast a shadow on land adjacent to the river (May 28, 1976) and on the river itself (June 28, 1977). As seen in Table 4-1, on both occasions the shadow radiances are much lower than the river water. Since the shadows and the river are surrounded by the same high albedo land, the higher river radiances must be attributed to water pollution.

4.3.8 Divide County

The radiances for the two points obtained at this site (the target is a lake 2 x 0.5 km about 500 meters from the Volz site) are both higher than the San Diego data, as shown in Figures 4-8 and 4-9. This was expected since the black and white prints show evidence of water pollution.

4.3.9 Hill County

This Volz site is about 8 km from a dammed river about 1 km in width. All the radiances, plotted in Figures 4-8 and 4-9, are higher than at San Diego. Water pollution is clearly seen in the Landsat prints upstream from the target area.

4.3.10 Toole County

It was originally planned to use a large (3 x 1 km) lake about 6 km from the Volz site, but it apparently dried up, so a smaller (0.5 x 0.5 km) lake about 3 km from the Volz site was used. Four of the six data points, shown in Figures 4-8 and 4-9, exhibit higher radiances than found at San Diego. The two points at 0.44N show good agreement with the

San Diego site, indicating that adjacent higher albedo land has perhaps little effect on the water radiance, and certainly has less effect than does the water pollution.

4.4 Radiance and Contrast Measurements in Urban Areas

In order to answer the question of the usefulness of radiance and contrast measurements to determine the aerosol content in urban areas, theoretical calculations were made, and Landsat 1 data over San Diego were analyzed.

The Dave program was used to compute the upwelling radiance in MSS6 as a function of aerosol content for several surface albedos for a sun angle of $\mu = 0.45$; a size distribution with $\nu = 4$, and a refractive index of $n = 1.5$, were used. The results are presented in Figure 4-10. It is seen that the radiance is most sensitive to aerosols for $A = 0$; at $A = 0.3$ the radiance shows no change with aerosol content, and at $A = 0.4$ the radiance even decreases with increasing aerosol content. The theory is supported by the Landsat 1 data obtained over desert ($A \sim 0.3$) and water ($A \sim 0$) surfaces, also shown in Figure 4-10. The experimental data show excellent agreement with the theoretical predictions at high and low albedos. Hence, the theory for intermediate albedos (urban areas) may be assumed to be representative of experimental data, i.e., the radiance over urban areas ($A \sim .15$) does not vary significantly with aerosol content.

The theoretical relationships, of course, assume that the surface albedo is constant. This is a good approximation for unpolluted bodies of water, and to a lesser degree the desert (rain, wind, and vegetation growth can affect the surface properties). However, in urban areas the surface reflectance can change quite rapidly, due to rain or dust-cover, and slowly, due to man-made changes in structures and surfaces. In addition, the effective reflectance will vary with sun angle

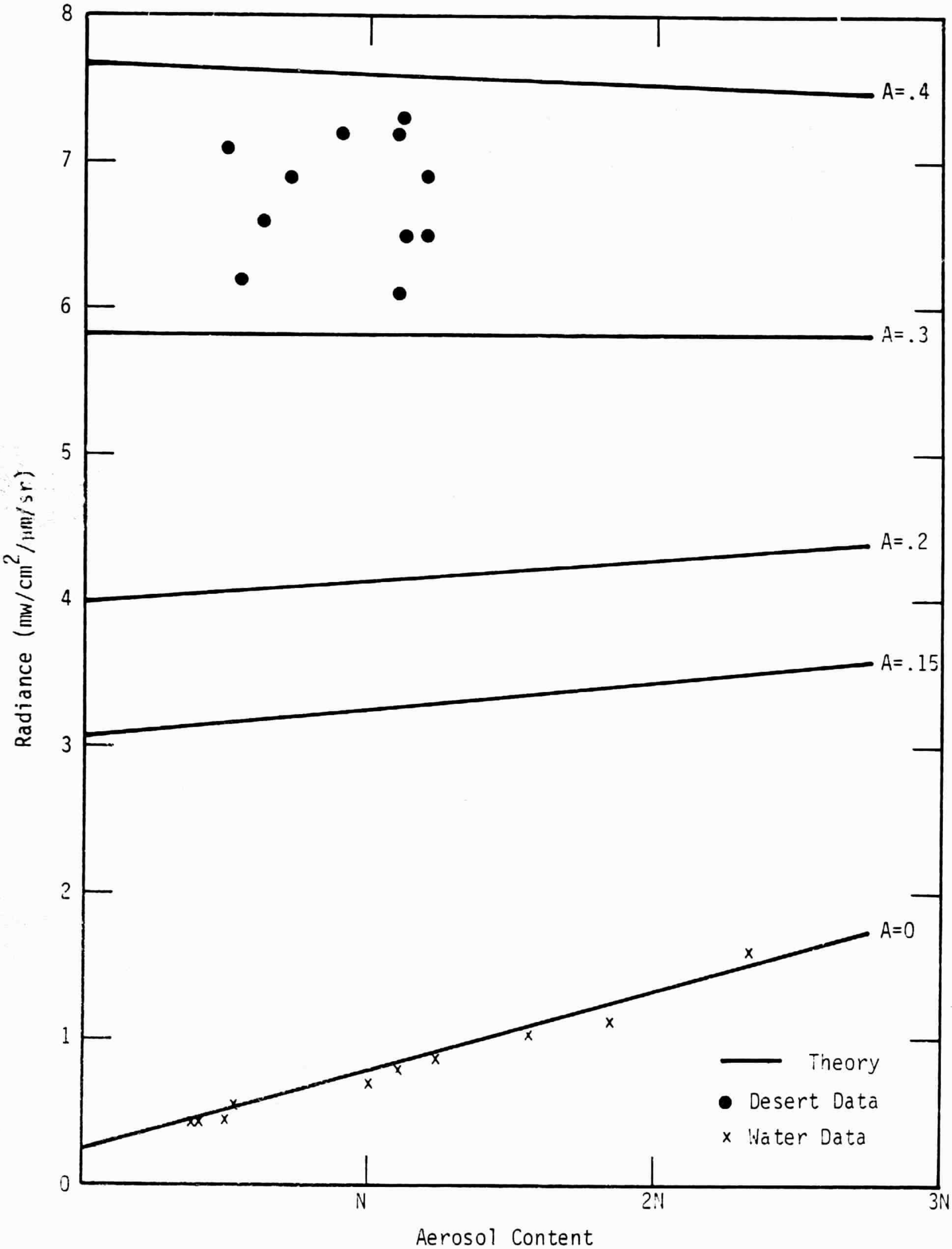


Figure 4-10. MSS6 Radiance Versus Aerosol Content as a Function of Albedo.

on a daily basis due to the presence of buildings, and on a seasonal basis due to the presence of vegetation. Hence, it is probable that the radiance over urban areas will vary more due to reflectance changes than to aerosol content changes.

The radiances over two locations in the San Diego urban area were determined for three consecutive overpasses in the December 1972 - January 1973 period. For these data the sun angle was approximately constant (62 - 63^o zenith; 146 - 151^o azimuth), so no significant effect due to sun angle variation is expected. The radiance in urban areas exhibits considerable spatial variation, and it is very difficult to locate exactly the same areas for each overpass; hence, some differences are expected in intercomparing the overpasses.

The spectral variations for the two locations for the three overpasses are shown in Figure 4-11. The spectral shapes are similar, but the radiance values show no correlation with the aerosol content for any of the four MSS channels.

In summary, the theory predicts, and the Landsat data verify, that over urban areas the radiance is not very sensitive to the aerosol content, and in fact is more sensitive to reflectance changes. Thus, it is concluded that the radiance over urban areas cannot be used to determine the aerosol content. Similarly, contrast between the urban area and a water surface is not useful, since any contrast change, due to aerosols, would be essentially all due to the change in the water radiance; in fact, temporal changes in the urban reflectance would introduce much larger changes in the contrast than would the aerosol content.

4.5 Surface Radiance Measurements

Three aircraft flights with the Exotech radiometer were made at the time of Landsat 2 overpasses. It was cloudy at the time of the first flight on June 10, 1975, in San Diego, so no useful aircraft or

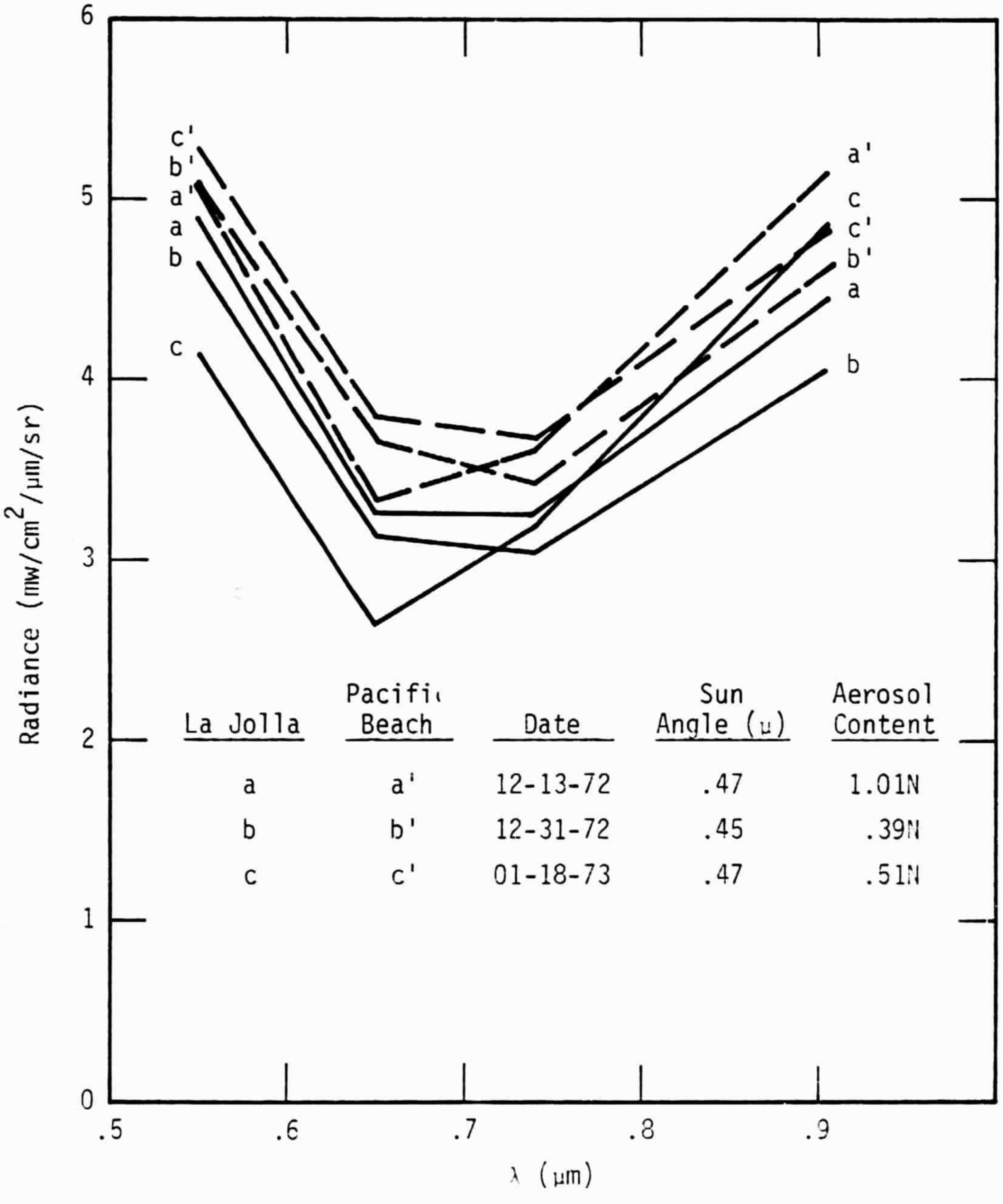


Figure 4-11. Measured Spectral Variation of Urban Radiance in San Diego Area.

satellite data could be obtained. Hence the flight was very brief and was used to check out the flight system. The second flight was on June 27, 1975, in clear skies at the Salton Sea. The third flight was on July 16, 1975, in San Diego under hazy conditions.

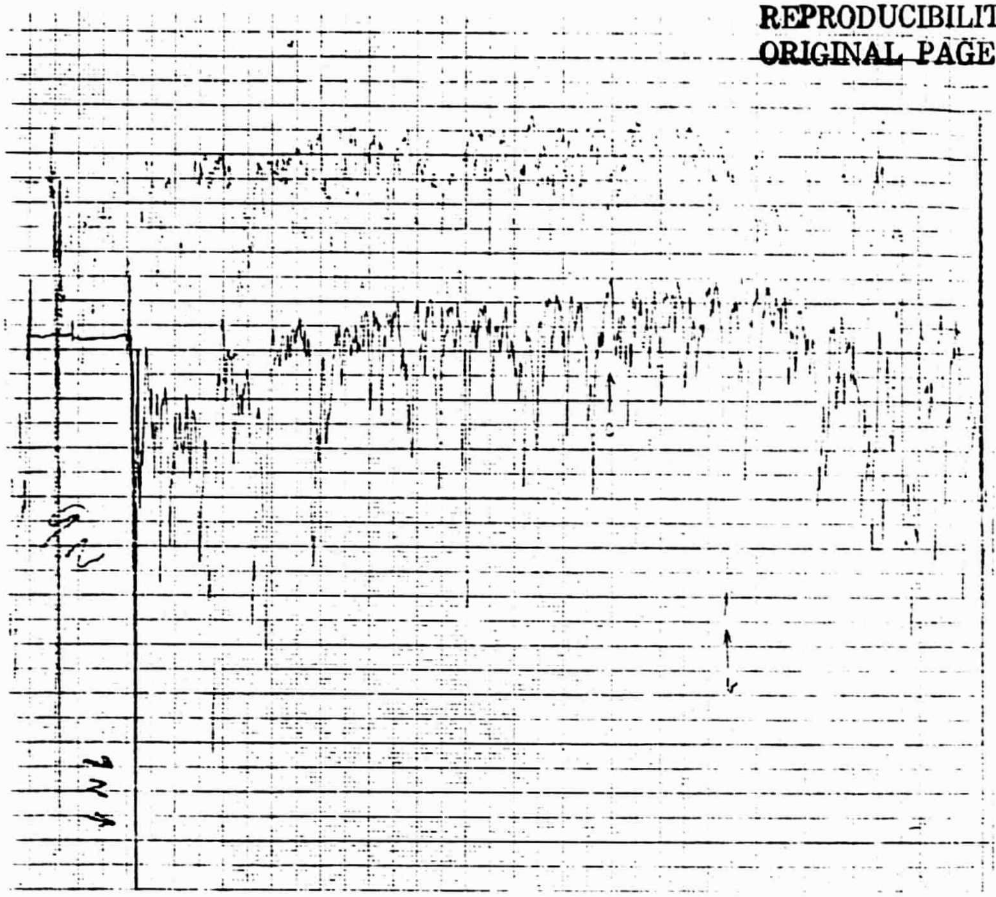
The analysis of the surface radiance measurements obtained on these flights raised several questions of interpretation, as discussed below. These questions together with the fact that the contrast technique is not useful (see Section 4.4), led to the decision not to pursue the aircraft measurements in this program.

4.5.1 Aircraft Data Analysis

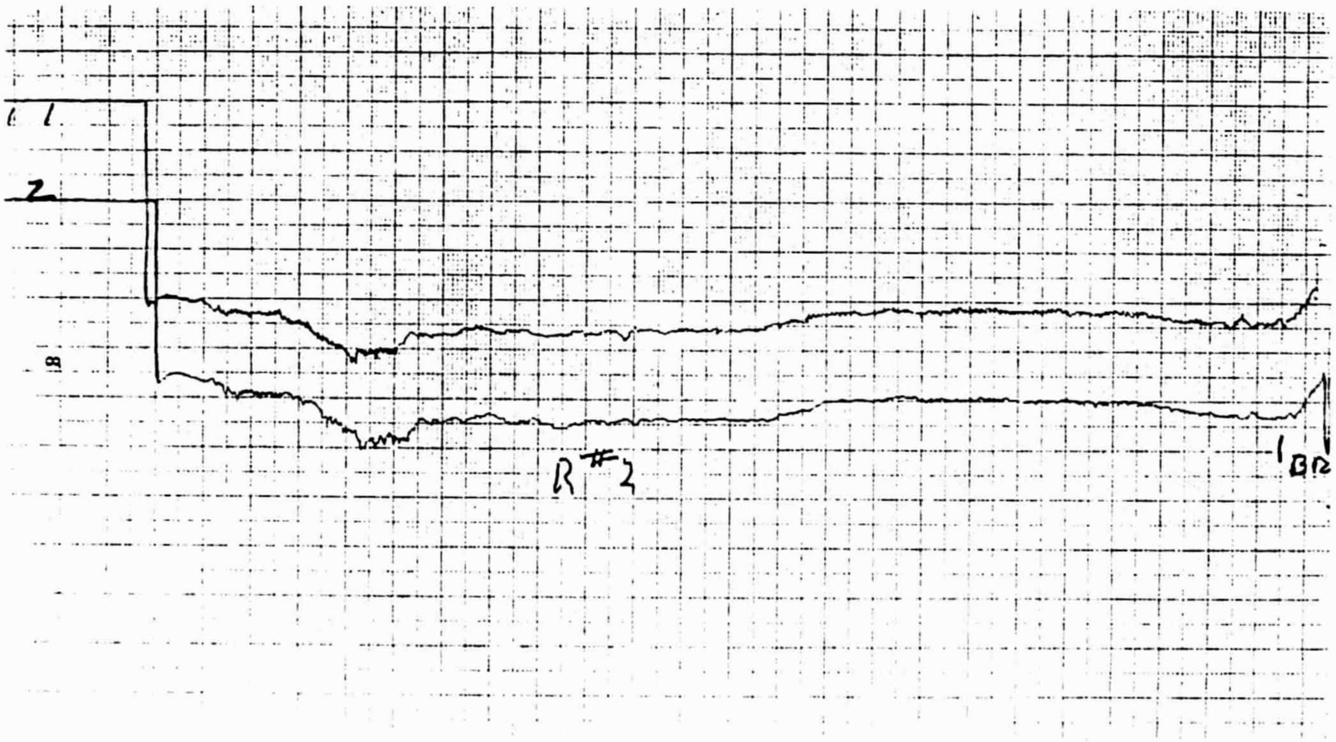
The measurements were made at 15, 30, 60 and 90 meter altitudes, with headings of about 315° and 135°. The measured radiances showed no obvious dependence on altitude (atmospheric thickness below the aircraft) and heading (scattering angle). Data were obtained over an area of about 2.5 km x 0.8 km within the Landsat target area.

The aircraft measurements made at San Diego under hazy conditions show wide variability in the radiance values. Correlating sharp peaks were observed in all four channels with amplitudes as great as five times larger than the mean value. These peaks had about 15 meter half widths, and are presumably due to sun glitter or patches of water with different reflectivities. However, the amplitudes of the peaks did not appear to depend on the flight direction, suggesting that sun glitter is not responsible. An example of the data is presented in Figure 4-12a, which shows the recordings for MSS4 and MSS5 obtained at 30 meter altitude over about a 2.5 km flight path (chart speed: 15 cm/min.; airspeed: 140 km/hour). These data are in sharp contrast to the smooth data of Figure 4-12b, obtained at the Salton Sea under the same conditions; visually, the water surface appeared similar on both occasions.

The spectral variation of the San Diego data based on mean values for each run (about 2.5 km) is shown in Figure 4-13a. The data show a slight tendency to peak at MSS6, but not so clearly as at the Salton Sea as shown in Figure 4-13b. MSS4 and MSS7 show about the same

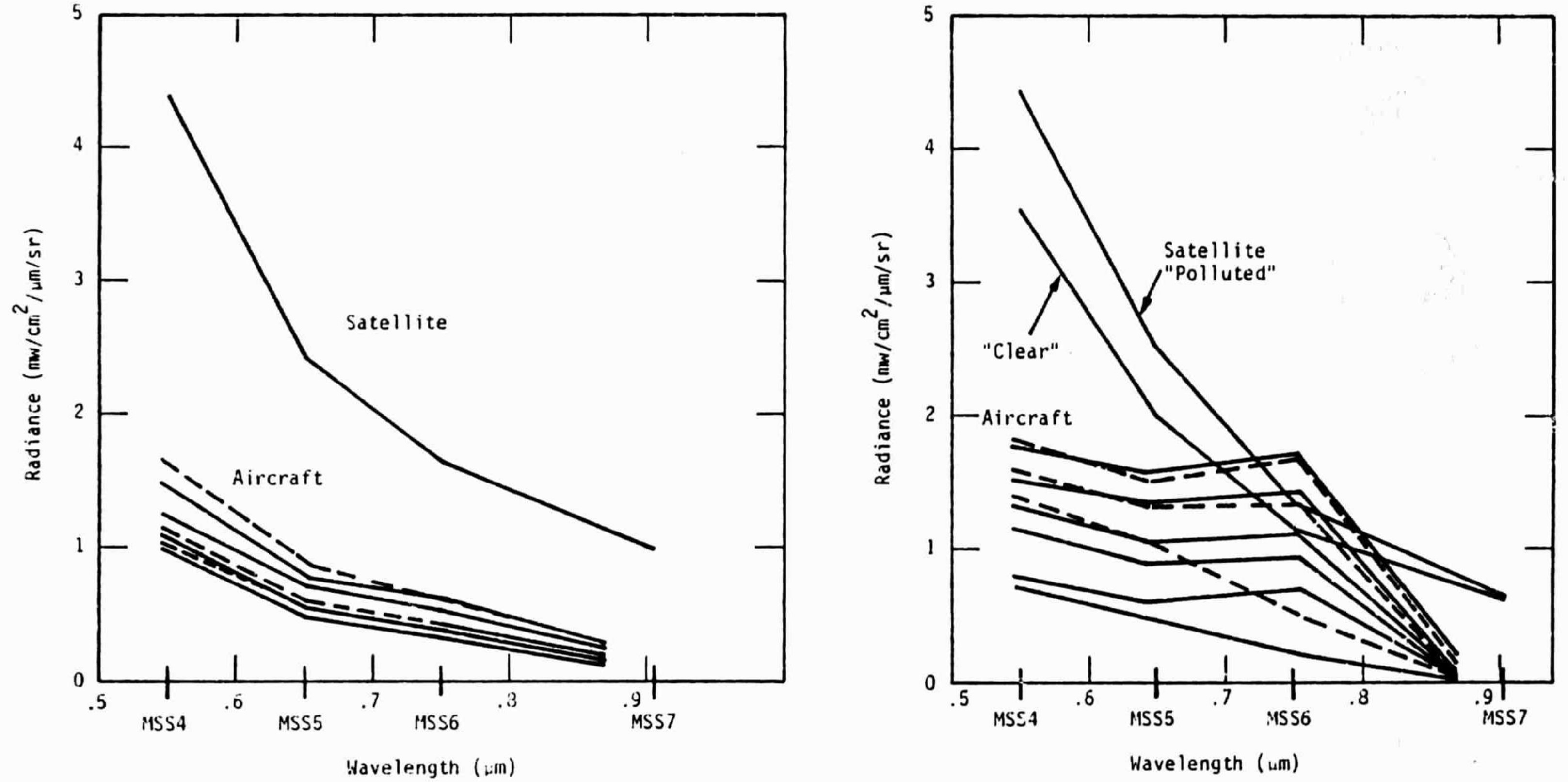


(a) San Diego Data 7-16-75



(b) Salton Sea Data 6-27-75

Figure 4-12. Aircraft Strip Chart Recordings of Surface Radiance.



(a) San Diego 7-16-75

(b) Salton Sea 6-27-75

Figure 4-13. Spectral Variation of Water Radiance Measured from Aircraft and Satellite.

radiance values, while the MSS5 and MSS6 values are generally lower at San Diego than at the Salton Sea. The peak in the spectral variation at the MSS6 channel in all but two sets of the Salton Sea data, suggest that the water was polluted. However, examination of the MSS black and white prints and the digital data for this overpass show relatively minor pollution. The Landsat data for the San Diego overpass show no evidence of pollution.

The satellite radiances which are shown in Figures 4-12a and 4-12b are expected to be larger than the aircraft values due to atmospheric scattering. The San Diego measurements look reasonable, but the Salton Sea satellite radiance is less than some of the aircraft values for MSS6, which is not reasonable. The Landsat data for both days show good agreement with the Landsat 2 aerosol content-radiance relationships, so it would appear that perhaps the aircraft data are in error. However, the Exotech MSS4 and MSS7 radiance values are similar at both sites, so there is no reason to doubt the Exotech MSS5 and MSS6 values at the Salton Sea. A satisfactory explanation of the Salton Sea data has not been determined. The difference in the spatial resolution of the MSS (70 meters) and Exotech (8 meters) does not account for the difference in radiances since the aircraft data were steady for distances of 1.5 km which covers many resolution elements of the satellite data.

4.6 Landsat 1 Data

A few sets of data were analyzed for Landsat 1 overpasses in this program, and are listed in Table 4-2, and plotted in Figure 4-14. It was found that in general these data obtained in the 1975-1976 period agreed well with those obtained in our original Landsat 1 study covering the period 1972-1973, although the later San Diego points show more scatter than the earlier data.

Some further observations on the Landsat 1 data are of interest. The data (MSS6 and MSS7 only, due to bottom reflectance effects) for Miami show excellent agreement with the San Diego data, whereas for Landsat 2, the Miami data tended to be lower, as discussed in Section 4.3.3. At

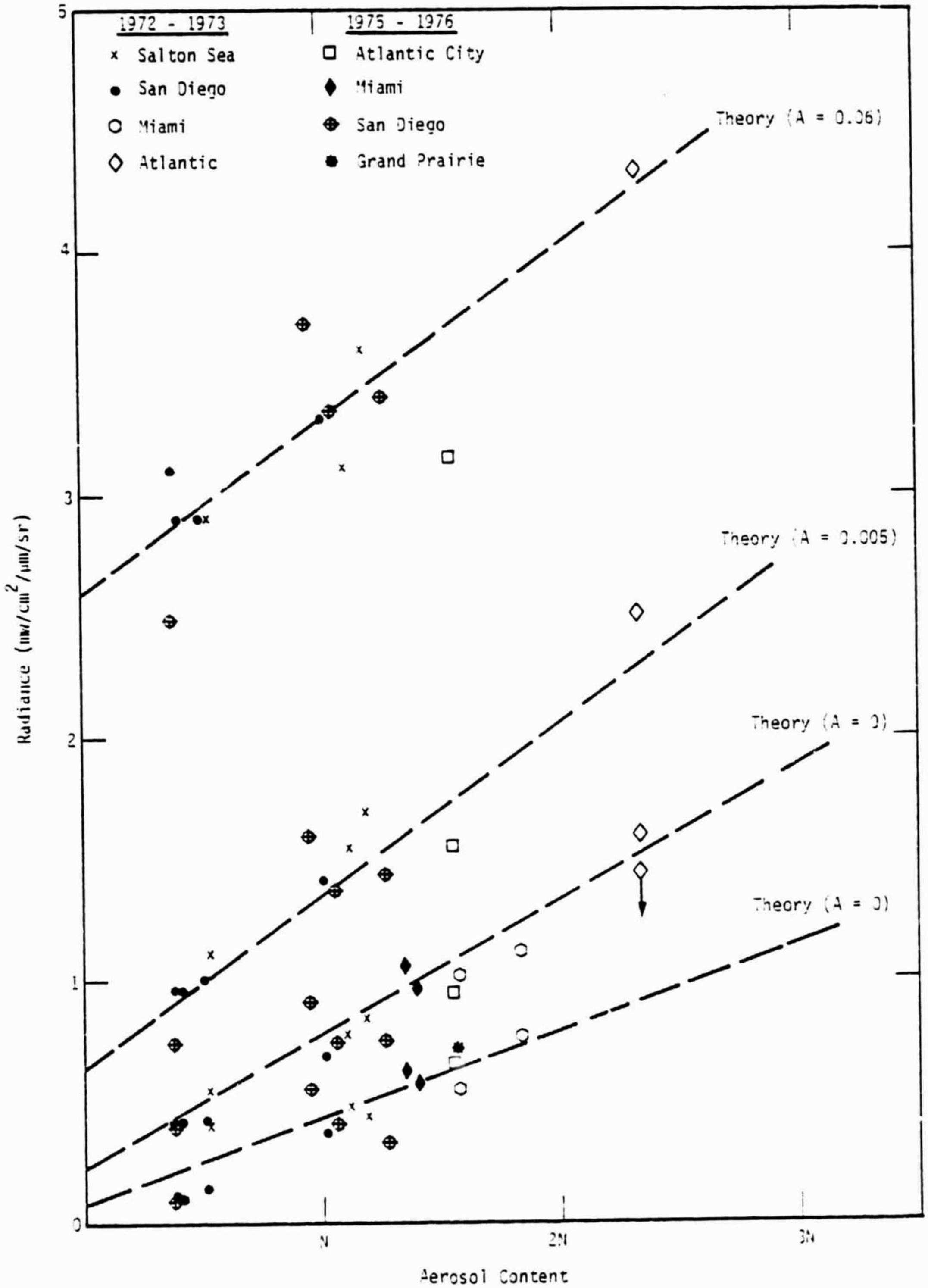


Figure 4-14. Comparison of Recent and Original Landsat 1 Data.

Grand Prairie where water pollution was clearly seen in the black and white prints, and clearly shown by the high radiances for MSS4, MSS5 and MSS6 in Table 4-2, it is seen that the MSS7 radiance shows good agreement with other unpolluted sites. This is because the radiation at longer wavelengths does not penetrate the water so much as at shorter wavelengths, and hence is not so influenced by water pollution. Thus it appears from Figure 4-14 that this channel may not be sensitive to water pollution, and hence could be used for measuring the aerosol content over inland bodies of water. It is unfortunate that this point could not be pursued with the Landsat 2 data due to its calibration problems (see Section 4.2). The one set of data for Atlantic City also shows good agreement with other sites for MSS7; and, as found for Landsat 2, the radiances for MSS4, MSS5 and MSS6 tend to be unexpectedly low.

It is noted that the radiance-aerosol content relationships for Landsat 1 and Landsat 2 are slightly different. This must be due to differences in the radiometric calibrations of the two satellites, and points to the necessity of precise radiometric calibrations of satellite radiometers if they are to be used in the future for aerosol measurements. Without precise calibration each satellite would have to be empirically calibrated with lengthy periods of ground truth measurements.

4.7 Discussion of Potential Problem Areas

Two potential problems were identified at the inception of the original Landsat 1 study: surface reflection gradients and sun glitter.

It is very difficult to assess the effects of surface reflectance gradients on the observed radiance over water surfaces. Theoretical calculations by Turner[28] and by Pearce[29] have estimated up to 70% increases in radiance over small low albedo areas (e.g. water) surrounded by high albedo surfaces. However, as discussed in Section 4.3, the Landsat results for small inland bodies of water suggest that the effect of the surrounding land is small.

Sun glitter was not definitely identified in any of the Landsat overpasses analyzed in this program except perhaps for one at San Diego as discussed in Section 4.3.1. This is probably due to the fact that the MSS views the earth very close (± 6°) to the nadir, where strong sun glitter is not anticipated. However, other satellite instruments, such as the scanning radiometer on the NOAA series, scan to the earth's horizon, and often show sun glitter effects in their output. Thus, while sun glitter is probably not significant in nadir viewing, as with Landsat, other satellite data should be used only when the radiometer is directed away from the sun.

Other apparent surface features of the ocean should be considered when this technique is applied to global monitoring. There have been reports of occasional observations of "wind-shadow" effects in the lee of islands (e.g. Strong et al.,[30] Needham[31]). This effect is generally attributed to a reduced sea state in the lee of the island, but it is suggested by Fett[32] that some of the effect could be due to air flow over the island modifying the atmospheric aerosols. Another effect, more obviously a surface one, is the observation of internal waves (e.g. Fett and Rabe[33]), but since this is apparent only in calm seas, and shows up only in sun glitter areas, it has no impact on the aerosol determination.

5. CONCLUSIONS AND RECOMMENDATIONS

A large set of Landsat 2 data, obtained at San Diego, showed excellent linear relationships, particularly for MSS5 and MSS6, between the radiance over the ocean and the atmospheric aerosol content. Two other data points obtained at Adrigole, representing a different ocean and a different ground-truth instrument, showed very good agreement with the San Diego data. Thus, it appears that the technique could be used for global monitoring of the atmospheric aerosol content over the oceans. The Landsat 2 results at Miami, in contrast to the Landsat 1 results, tend to show a different linear relationship, perhaps due to a different type of aerosol in that region. However, the Miami results must be used cautiously due to possible bottom-reflectance effects.

The results obtained at several inland bodies of water showed that MSS4, MSS5 and MSS6 cannot be used due to the effects of water pollution (natural or man-made) generally present. However, the Landsat 1 results suggest that MSS7, which operates at longer wavelengths, is not very sensitive to water pollution, and might be useful for inland measurements of aerosol content. The use of the longer wavelength would also minimize the effects of adjacent high albedo land, since atmospheric scattering is reduced at longer wavelengths. However, the results for MSS4, MSS5 and MSS6 indicate that this effect is small even at the shorter wavelengths.

It is recommended that this technique should be developed for operational use to monitor the global distribution of the atmospheric aerosol content over the ocean. Knowledge of the aerosol distribution and its variations will greatly aid climatic studies of long-term predictions of warming or cooling trends. Existing or planned satellites, with narrow bandpass visible radiometers, such as NOAA, GOES and TIROS N, can be used for global monitoring. However, if a choice of bandpass is possible, the Landsat results suggest that a bandpass of 0.1 μm centered

in the vicinity of 0.65 or 0.75 μm would be preferred. It would be desirable also to add a bandpass in the near infrared around 0.9 μm, since the Landsat 1 results indicate that the bandpass might provide information over polluted inland water as well as over the oceans. It should be noted that the radiance-aerosol content relationships for Landsat 1 and Landsat 2 were found to be slightly different. This must be due to differences in the radiometric calibrations of the two satellites, and points to the necessity of precise radiometric calibrations of satellite radiometers if they are to be used in the future for aerosol measurements. Without precise calibration each satellite would have to be empirically calibrated with lengthy periods of ground truth measurements.

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